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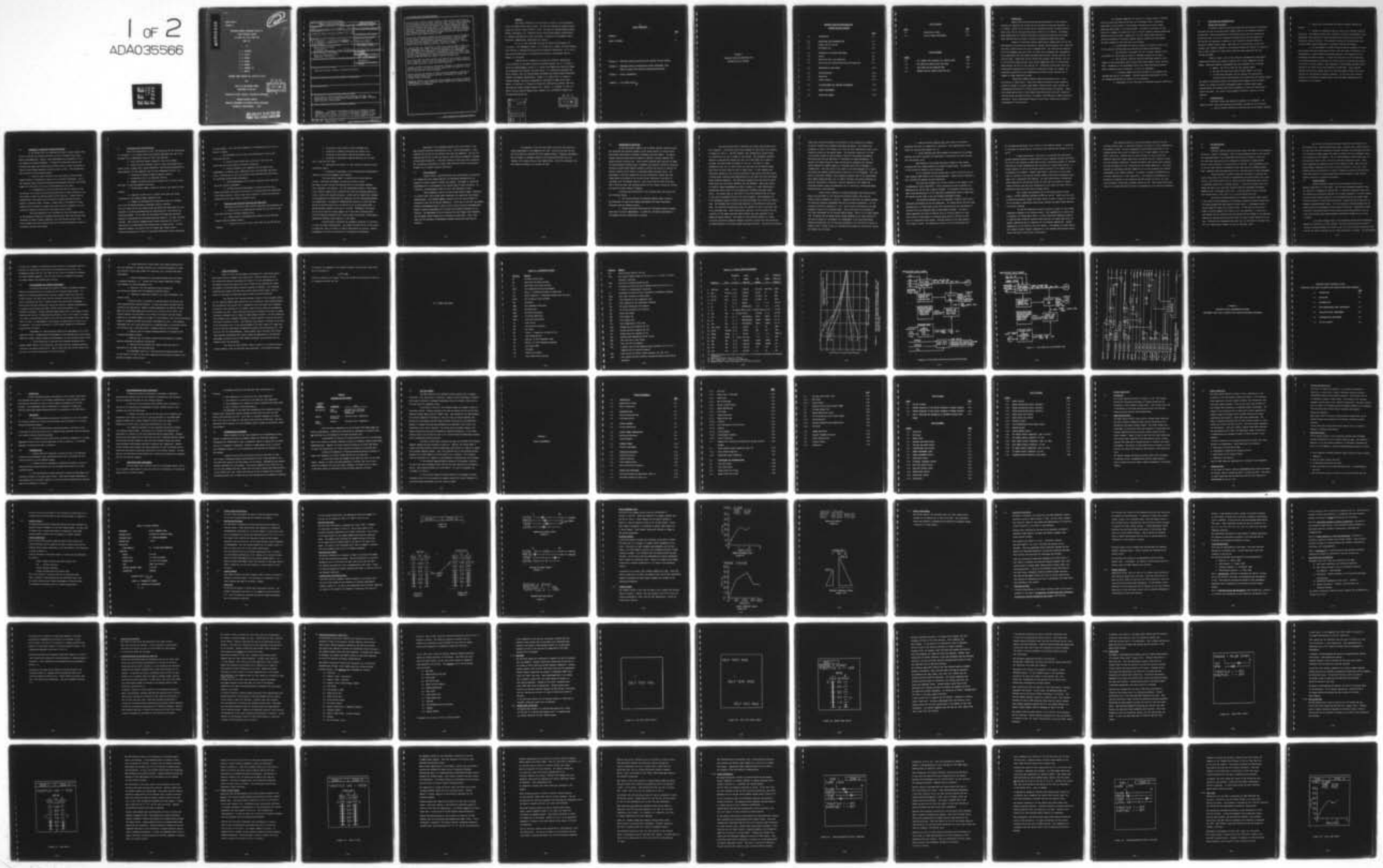

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INTEGRATED ENGINE INSTRUMENT SYSTEM (U)

FINAL TECHNICAL REPORT

(23 JUNE 1975 TO 22 JUNE 1976)

JUNE 1976

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Volume I contains the System Description of the Integrated Engine Instrument System (IEIS). In a effort to anticipate the needs of the flight crew and maintenance personnel in the 1980-85 timeframe, studies were conducted during the past five years to examine engine parameter

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definition and selection, sensor analysis, engine cycles, engine modeling, mission analysis, data trending, electronic fuel control, analog subsystems for vibration and turbine blade monitoring, display engineering, fault isolation techniques and human factors. The resulting baseline IEIS incorporates a variety of disciplines, including engine operation analysis, computers, multipurpose displays, data bus techniques, and data recording. Deck Launched Intercept and Subsonic Surface Surveillance missions were selected as typical applications for IEIS.

System user cost/benefit analysis and fault detection criteria presented in qualitative terms supplement specific system goals, such as system accuracy (±2% including sensors), probability of false alarm on the maintenance status indicator (.0005), self-test coverage (to a .98 confidence level) and system failure rate (4000 hours (MTBF).

A central data bus, interfacing the Electronic Engine Control (EEC), the Data Management Unit (DMU), the display processor, the data processor, the maintenance status indicators, the keyboard and the maintenance recorder, requires a relatively low transmission speed of 40 KBPS. This bus will also interface with other aircraft data busses and will probably conform to MIL-STD-1553 type command response configuration.

Flow charts show how IEIS software would monitor four aircraft operation modes, prestart, start, in-use, and shutdown, to present engine condition and initiate corrective action upon fault detection.

Computer processor and memory requirements necessary to implement the IEI Operating System and store the average engine model are shown to be met by a 32 bit word and a 44K word memory.

Display engineering concepts for IEIS have been developed, evaluated in human factors studies of pilot reaction, and modified to reflect the optimum display techniques.

Volume II contains four appendices which document the results of Phase V investigations in engine modeling, display human factors engineering and instrumentation requirements.

FOREWARD

This report represents the Final Report for Phase V of the Integrated Engine Instrument System (IEIS) Program. The work was performed by General Electric Company on contract number N62269-75-C-0359. The Naval Air Systems Command (NAVAIR SYSCOM), Washington, D.C., sponsored the work and provided support through Messrs. G. Tsaparas, AIR-340D and R. Rank, AIR-53351A. The Naval Air Development Center, Warminster, Pennsylvania, administered the contract.

Mr. W. G. Cole, AVTD NADC, has been the Naval Project Engineer for this effort. His management, Messrs. V. A. Frietag and E. Rickner, provided guidance. Their efforts in leading and monitoring this program are appreciated. Mr. W. Brietmaier provided assistance in the Human Factors efforts, with guidance from his manager, Dr. Hitchcock.

General Electric Company has utilized four different organizations in the execution of the Phase V portion of the IEIS program. Mr. R. L. Skovholt, acting as Program Manager, and Mr. W. S. Little, who prepared the technical summary and coordinated the technical activities and Mr. C. E. Buzzell who performed the sensor analysis task, are from Aerospace Instruments and Product Support Department (AI&PSD), Wilmington, Massachusetts. Messrs. W. A. Doerle and R. B. Cooper of Ordnance Systems, Pittsfield, Massachusetts, performed the human factor tasks. Messrs. M. Fine and R. E. Glusick of Electronics Laboratories, Syracuse, New York, performed the display hardware support task. Messrs. H. L. McManus, Jr. and I. E. Marvin from the Aircraft Engine Group, Evendale, Ohio, performed the engine conditioning monitoring work.

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TRANSIENT CONDITION MONITORING FOR ADVANCED MILITARY ENGINES

TRANSIENT CONDITION MONITORING FOR ADVANCED MILITARY ENGINES

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1.0 INTRODUCTION

Engine condition monitoring has become accepted as a cost-effective technique for improving the reliability and the safety of aircraft operations. It is, however, limited in its current form to steady-state models of engine behavior which allow only for long-term deterioration effects to be charted. Accordingly, usable engine data for condition monitoring is acquired during stabilized steady-state operation and is utilized to project corresponding steady-state trends.

Figure A-1 illustrates typical stabilization response data for the F101 PFRT engine for ten minutes of operation at constant PLA and constant inlet conditions following a throttle burst from idle to maximum speed. The stabilization characteristics are dependent upon the initial and final rotor clearances and, consequently, vary significantly with the engine operating history before, during, and after the throttle burst. Significant factors include the pre-burst power setting, the time at this pre-burst power setting, power setting immediately prior to the pre-burst power setting, the time at this setting, etc. Additional factors which affect the stabilization characteristics are mission oriented and include, for example, any significant variations in inlet temperature and bleed or power variation due to changes in flight speed and altitude.

Steady-state engine condition monitoring provides little, if any, anticipation of engine stall. Stalls are caused by propulsion system transients induced by changes in altitude, Mach number, flight altitude, power setting, and accompanying deficiencies in control system operation during the transient. Engine stall margin monitoring is a very complex task and had been previously recognized as being beyond the state-of-the-art in computer technology and in engine simulation techniques. Recent technological advances in both areas, however, have prompted a re-assessment of this position.

This Appendix summarizes the results of a limited study of transient condition monitoring funded by the Naval Air Development Center, Warminster, Pennsylvania, and performed by the Aerospace Instruments and Product Support Department under Phase V of the IEIS program. The specific objectives of this study are to examine the feasibility of an in-flight transient condition monitoring system which would include a capabilities for stall margin monitoring and to provide an estimate of "on-board" computer capacity required for this purpose. The basic premises of this study were the following:

1. A ground-based data analysis system is utilized for most or all of the long-term trending analysis associated with engine deterioration.

2. The functional requirements for the "on-board" computer are to be minimized by restricting its output to information needed by the pilot.

3. The "on-board" transient condition monitoring system is to be limited to those performance factors which affect stall margin, thrust, and fuel flow. Integration of the performance factors with safety monitoring features - such as vibrations and oil pressures - is not to be considered.

4. A relatively simple inlet model suitable for calculating inlet recovery and drag is to be assumed. Condition monitoring requirements for the air induction system and its controls is not considered.

5. Study depth is to be sufficient to establish technical feasibility.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 Summary and Conclusion

A transient condition monitoring system has been defined in preliminary form which can use an on-board digital computer model of the propulsion system to be monitored. Real-time simulation of the propulsion unit with its controls can provide the pilot with vital information on engine thrust and stall margins of the fan and the compressor in addition to the "condition" variables which are accepted as cockpit display items. Monitoring of inlet distortion, control performance, and transient response of the propulsion system will improve the effectiveness of fault isolation for those faults which have been responsible for most inflight shutdowns.

Table A-2 shows a list of the principal instrumentation requirements prepared with accuracy and response estimates for a typical augmented turbofan engine. Associated computer requirements have been estimated to be as follows:

1. Memory - 30K (36 bit words for the transient model)
2. Run time ten times better than an H6000 computer (2-4 mops)
3. An additional 30K memory will be required for preprocessing functions (which could possibly be overlayed with the transient model).

The system is considered practical for large military engines of the mid-1980's. However, an intensive five year development program to improve engine sensor characteristics and transient monitoring techniques will have to be undertaken to achieve this goal. The scope of this program is defined in Section 6 of this Appendix.

2.2 Recommendations

Additional studies and hardware development are recommended. The highest priority items requiring special development programs are the following:

1. Digital pressure sensors with improved accuracy and dynamic response.

2. Digital fuel flow sensors with improved dynamic response and accuracy.

3. Analyses of integrating digital controls and transient condition monitoring. (The General Electric AEG is presently involved in development of the Kalman-Bucy filter approach to Failure Indication and Corrective Action within the digital control functions. This approach uses most of the same sensors and transient model features applicable to transient condition monitoring.)

4. The development of systems concepts should be extended to provide more detailed distortion predictions from the inlet duct model (in addition to or complementary to engine distortion measuring features), and integration of all performance and safety features. A review and evaluation of service experience is considered necessary for assessing the relative worth of modeling and trending of the inlet duct and controls. Some expansion in the 30K memory estimate may be required if the value of the inlet modeling is established. Basic drag and recovery functions now require about 2% of the total memory or about 6% of that allocated to the modeling of physical processes. If the inlet were allocated one-third of the physical processes space, the total memory requirements will increase by 8 to 10 percent.

3.0 APPROACHES TO TRANSIENT CONDITION MONITORING

At the present time, two approaches are used to monitor engine stall. The first involves the attempted detection of stall "warning" noises using special instrumentation. However, these measurements are considered to be in the category of research phenomenon. Although data taken under special test conditions has shown that warning noises characteristic of stall can usually be found in a multi-stage compressor operating close to stall, this approach has been rejected for the following reasons.

1. With low inlet distortion, the stall margin at which warning signals develop is considered too small to be a practical measurement. Due to the relatively rapid transients encountered during engine operation, the warning signal will often occur too late to allow prevention of the stall.

2. The magnitude of the inlet distortion and the location of the low pressure cells within the distortion pattern have a strong influence on the stall margin at which the warning signals can be detected. A sensor which is influenced by a low pressure cell can receive a signal even when the stall margin is relatively large. Whereas, a sensor which is influenced by a high pressure cell can receive no signal until after the stall breakdown is too far advanced to respond to correction by the engine control system.

The second approach is the calculation of the stall margin, which is the difference between the transient operating line (TOL) and the stall line. Due mainly to aging of engine components, both the TOL and the stall line, tend to migrate and these migrations must be continuously monitored in order to accurately calculate stall margin.

3.1 Monitoring Stall Line Migrations

While the investigation of stall line migrations has not been pursued in a systematic way, present theory and available experience have led to the following list of hypothetical causes of stall line migration:

a. Inlet distortion pattern, magnitude, and rate of change.

b. Steady state and transient errors in stator positioning due to control errors, rigging, wear, design compromises, installation problems (such as steam ingestion, hot gas ingestion, and the inlet temperature profile), etc.

c. Variations in engine-to-engine compressor quality.

d. Accumulation of dirt on compressor airfoils.

e. Changes in blade-tip and seal clearances due to throttle bursts and chops, or when environmental conditions.

f. Foreign object damage, erosion of airfoils, and erosion of seal surfaces.

g. Ingestion of water and ice crystals which upset the design relationship in the stage-by-stage compression rate.

h. Changes in interstage bleed proportions either for "working" air or for off-design matching of compressor blocks or boosters.

This list shows clearly that engine design and application differences are very important in choosing instrumentation for monitoring stall line factors and predicting changes. Not so clear are the technical problems and associated expense of ascertaining the correlation functions (Mach No., altitude, and power setting). Many arbitrary judgements must be made concerning the control of some factors by design methods and leaving others to design margin. In later generation engines, more factors will be brought under design control. Correlation functions will have to be developed during early service experience

with new engines. Also, arbitrary judgements on instrumentation level will be subject to change.

The recommended level of stall line monitoring for initial TCM projections follows:

a. Provide on-line predictions of the stall lines from the stored data and the in-flight deterioration conditions.

b. Provide trending of the compressor and fan quality from measurements of pressure ratio, temperature ratio, corrected RPM, and stator error. Correlations of stall line variation with operating efficiency should be established during engine development.

c. Provide measurements of the stator transient errors and trending of the controls performance.

d. Provide distortion measurements to predict the stall line effects and monitor the trend in the severity of the application and degradation of the inlet controls. Special logic may be required to record the distortion conditions and the inlet control transient errors.

3.2 Monitoring the Transient Operating Line Migrations

Important factors which cause transient operating line migrations are:

a. Control errors in scheduling and feedback of main fuel flow and core stator position (including rigging errors).

b. Control errors in scheduling and feedback of A8 and WFR when using A8 position feedback control.

c. Variations in aircraft bleed; anti-icing; and cooling and seal leakages.

d. Variations in high pressure turbine diaphragm area.

e. Variations in combustor efficiency and pressure loss.

f. Variations in fuel specific gravity and heating value.

g. Variations in afterburner light-off RPM (also cut off RPM) and in light-off fuel flows.

h. Variations in A8 preset (or logic failures) leading to harder afterburner lights.

i. Variations in performance of rate-limiting and synchronization functions in the A8 and augmenter fuel systems.

The above factors cannot be measured with state-of-the-art sensors. Additional development TOL monitoring should include providing corrected airflow and pressure ratio for each engine component (fan, compressor, and booster). Air flow measurements require a large number of air pressure samples from a distorted flow field with shifting patterns in order to achieve the required accuracy. Airflow can be trended with a minimum of instrumentation providing that the conditions for the trending measurements are standardized. An example of standardization would be to record TOL data during the throttle burst prior to take-off at low or zero ground speed. A ground shutdown transient could also be recorded. Knowledge of the mission mix of an aircraft will likely suggest one or more other transients which could be frequently monitored with a narrow range of conditions without adding unnecessary transient cycles and wear to the engine.

Corrected RPM is considered an acceptable alternative to corrected air flow for sensor considerations. The sensors for RPM tend to be less costly, to weigh less, and to be easier to install than sensors for airflow. However, measurements of airflow are preferred for the physical significance.

Measurement of the component pressure ratios are subject ot the same pressure distortion considerations as the airflow measurements. Static pressures may be used for the pressure ratio when the geometries (A41 for the compressor and A8 for the fan) ,are known or when airflow is measured (reference corrected RPM alternative). Distortion effects are less with static pressures, but of sufficient importance to require that distortion factors be controlled through use of standard transient monitoring.

3.3 Fault Isolation

Pressure ratio, corrected airflow, and corrected RPM are sufficient for trending the stall margin function, but additional parameters will be required to isolate causes of reduced stall margin. The number of additional measurements will be determined by the required level of fault isolation. As a baseline, the measurements listed for stall line TCM would be used.

Other parameters, such as the anti-icing "on-off" signal, indication of aircraft bleed, and aircraft power extraction, are needed for stall margin identification. For turbofan engines, pressure ratio and airflow should be obtained for both the fan and the compressor. In the case of the F101 type engine, pressure instrumentation may be used in lieu of special airflow instrumentation. However, separate measurements for fan inlet and discharge pressures will be required. The measurement of A8 is desirable for stall margin fault diagnosis, but the engine control signal will be suitable for most cases. Power level angle will be necessary if nonstandard transient monitoring conditions are required.

The diagnosis of the fan stall margin on an F101 type engine will require measurement of the augmentor fuel flow. Both this flow and the main fuel flow should be obtained from fast response sensors. Response requirements may be relaxed for standard transient event recording providing that the response of the sensor does not vary significantly. Fuel flow instruments will need improved response to be suitable for TCM.

4.0 DESCRIPTION OF THE SYSTEM

An on-board digital computer and an engine transient simulation model are considered the essential elements of any system required to provide timely and accurate monitoring of transient performance and stall margin. The engine thermal properties model stored in memory is needed to develop transient data using previously recorded data. This on-board transient model provides the means for storing engine characteristics, eliminates the logistics problems of exclusive reliance on ground based computer analysis, provides the ability to consider the effects of FOD's and the effects of exceeding engine operating limits. The achievement of the full capabilities of such a system will require that some timing device be provided to set certain initial conditions in the model in accordance with the shutdown interval. This device need not operate for more than a few hours after each shutdown because the full engine cooling will obviate the need for further timing or indexing.

A multiple mode functioning of the transient model was selected for the following reasons:

1. The obvious approach of comparing measured engine variables was determined to require more engine measurements and higher measurement accuracies than are deemed practical.

2. Without multi-mode functioning the off-design component mapping would have to be more comprehensive. In addition, the memory requirements of the computer would be significantly increased.

The two principal modes of operation are termed "quasi-steady state" and "transient". The overall system block diagrams for these modes are presented in Figures A-2 and A-3. Internal computer logic automatically switches modes as a function of the rate of change of PLA and RPM. The independent variables required to appropriately address the basic cycle deck model are as shown in the upper left hand corners of Figures A-2 and A-3. In Figure A-2 these variables are PLA, Mo, To, and Po which are sufficient for the nominal engine model after the timer index is reset at engine start. In the transient mode constraints imposed by rotor inertias and control lags require additional inputs to define model conditions and synchronization of the model with time constrained engine feedback parameters. The additional parameters over and above the quasi-steady modes are rotor speed, WFR/Ps3B, PRF, and WFM/Ps3B. These model inputs are based on engine measurements as shown in Figure A-3. Model functioning is accomplished using a model for each engine mode (transient and quasi-steady state). The primary mode for each model is real-time simulation and its output in this mode is designated as ZNC on the block diagrams. ZNC encompasses all of the parameters needed to monitor the engine performance and correct for sensor lags. The secondary mode of each model operation is the derivative calculation mode. The derivative calculations occupy the computer for only a very small part of the operating time. These calculations, therefore, do not interfere with the continuity of the memory functions which simulate the state variables of the engine and engine controls. The output for the derivative mode(s) is a table of partial derivatives updated at frequent intervals to assure that the derivatives are representative of the latest engine operating conditions. The partial derivatives

drawn from a scratch-pad memory are multiplied by the differential increments in control variables and component performance parameters. The products are increments in thrust, stall margin, etc. which are then algebraically added to the simulation values for the nominal engine. The resultant values are to be used in the cockpit display as best estimate of actual on-line engine performance. The display may also use ZNC values as references for normal performance. If desired, the actual values for thrust and T4B may be displayed with reference values computed for nominal engine at a reference power such as "maximum" or "maximum dry". This last option is not shown in the block diagrams but is available within the computer specifications of Section 6.0 of this Appendix. This last option is achieved by adding a third sequencing computer mode to the quasi-steady state engine simulation mode (i.e. at regular intervals the primary simulation is partially interrupted to calculate a case for hypothetical PLA change; the resulting reference thrust and temperature will be stored in a scratch-pad memory between periodic recalculations).

Control errors (relative to normal performance) and distortion parameters are established by the "Sensors and Deviations Model" which has the function shown in Figures A-2 and A-3. Figure A-4 describes the general approach for measuring transient performance data and the distortion parameters. All calculations indicated on Figures A-2 A-3, and A-4 would be performed by the same computer as used for the transient model. Thirty one sensors are indicated as the likely requirement for an advanced fighter engine. Some or all of these sensors may be shared with the engine control system depending on the sophistication of the control design and requirements for independence of the monitoring system. Sensors providing data for the distortion parameters, P12, and P3/P25 are shown in groups of four. Groups of four are considered the minimum for any practical system; the reasons are as follows:

1. Fewer distortion sampling zones would result in distortion parameters which are too insensitive or inaccurate - more sampling points would usually be required where margins are low

2. Fewer sampling zones would degrade the accuracy for the average pressure and overly compromise the usefulness of calculations for inlet recovery and core pressure ratio.

Some features of the system described in Figure A-4 may require discussion even for readers familiar with engine systems design. The remainder of this section is devoted to this discussion.

P12 is calculated from an average Ps12 in order to avoid the use of total pressure rakes ahead of the rotating machinery. (Rakes would be required to get a satisfactory average for pitot pressures).

The distortion parameter for the fan is based on the highest of four circumferential ratios (Ps14/Ps12). Static pressures are used to minimize the sampling errors and the rake integrity problems. An alternative distortion parameter using max-minus-min of Δ P/P (ΔP14/Ps14) measurements would be competitive and should be given study in any full-fledged development program.

The distortion parameter for the compressor is based on Δ P/P and is definitely preferrable for the core compressor. The reason derives from the slope characteristics of P3/P25 when plotted from corrected speed (the alternative of corrected flow was eliminated based on measurement problems). With multi-stage compressors the slope of pressure ratio to corrected speed is so high that an error of one percent in corrected speed results in an error of one-third of acceleration stall margin. Ps3B was selected as the base pressure for the Δ P/P ratios. The advantage for Ps3B is its close correlation with

PT3 and sampling advantages of wall statics in the combustor plenum. A correction is calculated for burner Mach No. variations using computed best estimates for T41 and T3.

A signal proportional to CDP bleed is calculated from differential pressure measured between the bleed manifold and the combustor pressure tap (PS3B). The ratio of this pressure to PS3B would provide a quantitative measure of "customer" bleed and anti-icing (assuming that both of these use a common bleed source). A similar approach is used on the GE F101 engine to provide a trim signal for the acceleration fuel schedule. Another bleed signal in addition to the one shown might be required if the aircraft requires another bleed source (compressor inter-stage) with a significant flow capacity. For some installations a satisfactory bleed signal may be provided more simply by using only the presence or absence signals available from electrical energization of the bleed flow rates which are predictable from on-off data from the supply valves.

Error signals are generated for the following principal control signals: (AP/P)F; WFM/PS3B; WFR/PS3B; $NF/\sqrt{\theta}$; BF; and BC. These errors are used to evaluate performance changes from model values as shown in Figure A-4 and would also be recorded at appropriate times during transient and quasi-steady operation for controls trending.

T12 and T25 temperature sensors are shown in Figure A-4 with dynamic compensation computed by the transient model. This compensation for sensor lags is necessary for thermocouples, RTD's, or other traditional temperature sensors. If speed-of-sound ultrasonic sensors become practical for engine application the dynamic compensation may be eliminated for the affected temperatures. Dynamic compensation is also shown for fuel flow sensors. The response for these sensors will probably require computed compensation if the response rates deviate significantly from those of the control counter-parts.

The concluding feature in the TCM preliminary design is the data recording function which is considered necessary for access to a more comprehensive data analysis system. The more comprehensive system would perform much of the trending analysis which would be impractical for a flight computer in the early 1980's time period. Recorded data as shown in Figure A-4 would include the operating conditions, sensed engine data, and control "errors" relative to objectives as defined by simulation. Recorded variables would include other variables not shown in Figure A-4 (e.g. vibrations and lube system parameters). The system concepts are preliminary and were prepared as an aid for estimating the probable requirements of an airborne computer. The amount of engine instrumentation may be overly ambitious for a first application. The distortion instrumentation is probably not essential to the simulation and TCM concepts but may be the extra that would make a large basic investment really pay off. Stall margin predictions would be of limited reliability without an accounting for the distortion influences.

5.0 TCM APPLICATIONS

5.1 Background

Transient condition monitoring (TCM) using a full model of the propulsion system has a number of advantages. Most of these advantages relate to the accuracy and comprehensiveness of the information which would be provided to the pilot. The traditional approach does not encompass the influences of engine thermal history, inlet distortion, or deterioration of controls. Other advantages accrue to the real time display of information rather than long term trending analysis only. Examples drawn from experience serve to illustrate some of these advantages.

Flight testing of the XB70 at Mach Nos. exceeding 2.0 revealed that stalls could persist for intervals of approximately one minute before pilot recognition. Such "soft" stalls occur at reduced corrected RPM and may cause failure of compressor blades due to rotating stresses. A TCM would recognize that stall margin had gone to zero and could logically associate subsequent performance anomalies with a continuing "soft" stall. A warning display would be provided with instructions to clear stall (i.e., chop and advance throttle).

Bird-strike testing conducted on an advanced turbofan engine caused a stall which cleared immediately, but resulted in markedly reduced fan RPM (with core speed automatically maintained at pre-set value). A subsequent action to restore target fan speed led to another stall. In this case the stalls were caused by severly damaged rotor blades in the core compressor. A reduction in stall margin and core corrected flow had resulted from the damage to the compressor. Clearing the rotating stall would have failed to restore normal operation in this case. Procedures and recommendations should call for shut down of an engine after one or two unsuccessful attempts to clear an "apparent" stall.

The files of the FAA also have many cases which are instructive to the objectives of a condition monitoring system. Excerpts from a report #FS-140-72-2 show that the three categories of highest incidence rate performance deficiencies requiring in-flight engine shut downs in calendar 1971 were compressor stall, slow acceleration, and flameout. For all turbine-powered aircraft there were 357 in-flight shut downs in 1971, with 282 in the three categories listed. These three categories are addressed by the special features of TCM. Most of the 282 cases probably originated in the area of controls and most, if not all, could probably have been anticipated if a model of engine and controls could have been effectively applied to distinguishing deteriorating parameter trends from the complex variations in operation environment.

5.2 Cockpit Display

Display features discussed in IEIS Final Report Phase IV are generally applicable to a TCM system. The only new performance parameters which are definitely recommended are SMF and SMC. A distortion display(s) should also be considered as potentially desirable for in-flight diagnosis of low stall margin. The stall margin displays should be of the bargraph form with the normal range defined and should be called only when desired. Exceptions would be made for low margin(s) exceeding normal limits. For this situation a warning message would be supplied along with bargraphs of SM and possibly distortion. Consideration might be given to continuous display of stall margin during combat maneuvers, and the pilot could possibly gain greater maneuver performance through the use of such a display.

An on-board computer model of the propulsion system should considerably enhance the accuracy of a thrust display. The pilot survey reported in Phase IV revealed a strong preference for thrust as one of the two principle flying aids (fuel flow was the other) providing that the thrust indication is accurate. The TCM approach

outlined in this report is considered the most accurate of the methods which are practical for operational use and would be satisfactory for pilot use. The recommended display would be a bar graph for net thrust with markers for maximum dry and/or maximum augmented. Fuel flow should also be displayed with markers for normal range at the existing power setting.

6.0 TCM DEVELOPMENT AND COMPUTER REQUIREMENTS

A practical TCM system will require a sizeable development program to improve the state-of-the-art for sensors and for transient engine models. In general, the available sensors which have fast response capabilities lack sufficient accuracy, and those which have the required accuracy are inclined to be costly, unreliable, and slow. Transient models also need further development because there has been insufficient testing with quality transient instrumentation to establish stall margins and engine thermal conditioning effects (i.e. transient clearances). Current transient models applied over a wide range of flight conditions are capable of predicting stall margin to only 5 or 10 points in accuracy (e.g. given a predicted stall margin of 25%, the true stall margin lies in the range from 20 to 30%). An improvement in the accuracy of predictions by a factor of 2:1 is essential. The accuracy required for a given engine depends on the available margin and the tolerance.

Development of a TCM system must parallel the development of its "host" propulsion system. Accomplishing the development of the transient model would require analytical studies, engine testing, and data analysis for the following areas of study:

1. Better definition of the stall line including variations due to Reynolds Number effects, inlet distortion, off stator effects, transient operating conditions, and engine deterioration. Some of these have been studied analytically. All need to be tested and subjected to further analysis.

2. Better definition of those steady state engine characteristics which are important in transient modeling (e.g. low speed performance) or which are difficult to test under normal test conditions (e.g. corrected high speed performance).

3. Better determination of those model features which are unique to transient operation, i.e. thermal heat soak, engine dimensional changes, time constants for various phenomena, etc.

4. Modeling of the instrumentation system considering such factors as response time and temperature gradient effects.

5. Modeling of installation effects, e.g. inlet performance, and maneuver loads.

A parallel effort is necessary to optimize model size and run time while maintaining the required accuracy. To reach these goals the model must be tailored to the application. Based on current experience, a one percent accuracy model for an F101-type engine can be sized to fit in 30K of 36 bit words. The required computer run time needs to be a factor of ten better than the current capability of the H6000 computer (2-4 mops) in a mini-computer (this provides sufficient margin to accomplish on-board data analysis requirements as well). The estimated development cost for a first application of a transient model is two million dollars (1975 dollars) over a five year period. Estimated costs are the following:

- 100K per year for testing (assuming benefits of integration with an engine development program).
- 200K per year for analytic studies and data analysis to improve modeling techniques and empirical correlations
- 100K per year for analysis and computer operating costs for optimization of the model size and efficiency.

The development cost for a second application transient model would be less than half of that for the first, assuming that the propulsion system is not radically different from the first.

7.0 SENSOR REQUIREMENTS

Table A-2 lists the performance requirements for a TCM system sensors which would function throughout the flight map of a typical fighter aircraft. The accuracy and response requirements are known to be very challenging for the environment in which the sensors will have to function and tempering the engine environment by selecting highly favorable locations is unlikely. The instrument operating scale ranges (over which the accuracy specifications apply) could be reduced by limiting the flight map range for selected display functions.

The effective time constants defined in Table A-2 were evaluated using an F101 transient engine model modified for use in preparing a VFAX fighter proposal. The acceleration time (ground idle to maximum dry) for this engine with redesigned acceleration fuel schedule was 4.0 seconds. Data from this model was supplemented with engine test data. Model transients were used to determine lag errors in sensed variables at maximum rates of change for these sensed variables. The lags (effective time constants) were in general calculated as those required to keep the lag errors less than 0.5 percent of point. (The effective time constant is defined as the ratio of the lag-induced error to the rate-of-change of the input signal for a ramp input which is sustained long enough to essentially stabilize the lag-induced error (see any basic text on servomechanisms). Errors greater than 0.5 percent were allowed where response requirements were clearly beyond the capabilities of conventional measurement principles and for these sensors calculated lag corrections must be computed within the TCM system.

The effective time constants listed in Table A-2 for pressure sensors include pneumatic lines and manifolds where applicable. For estimation purposes

the dynamics of a pneumatic line (constant diameter without intake restriction) may be calculated as:

$$(e)^{-\tau s}/(1+\tau s)$$

where τ is defined as the length of the line divided by the velocity of sound for air temperature inside the line.

8.0 FIGURES AND TABLES

TABLE A-1 - DEFINITION OF TERMS

Notation	Meaning
A8	Jet Nozzle Throat Area
BF	(Beta-Fan) Fan Stator Setting
BC	(Beta-Core) Core Stator Setting
CCDP	Core Compressor Distortion Parameter
Δ	Delta -- A difference between two quantities
ΔP	(Delta Pressure) -- Difference between total and static
$\Delta P/P$	ΔP divided by static pressure
ETA	Efficiency
ETAC	Core Compressor Efficiency
ETAF	Fan Efficiency
ETAT	HP Turbine Efficiency
ETA2T	LP Turbine Efficiency
ETAR	Inlet Duct Ram Recovery
FG	Gross Thrust
FDP	Fan Distortion Parameter
FN	Net Thrust
θ	(Theta) -- Temperature divided by 518.7
Mo	Free Stream Mach No.
M25	Mach No. at Core Compressor inlet
M3	Mach No. at Core Compressor Discharge
NC	Core Speed (RPM)
NF	Fan Speed
PB	Bleed Port Pressure
Po	Free stream static pressure

Notation	Meaning
P12	Total Pressure ahead of the fan
PS12	Wall Static Pressure ahead of the fan (A, B, C, D refer to circumferential locations)
PS14	Wall Static Pressure behind the fan
P14	Difference of Total and Static Pressures behind the fan (A, B, C, D) refer to circumferential locations)
P3	Difference of Total and Static Pressures at Compressor Discharge
PS3B	Wall Static Pressure for Main Burner
P25	Total Pressure at Core compressor inlet
P3	Total Pressure at Core Compressor discharge
P49	HP turbine discharge total pressure
P56	LP turbine discharge total pressure
PLA	Power Lever Angle
SMF	Stall Margin Fan
SMC	Stall Margin Core
T12	Total Temperature at fan inlet
T12L	Sensing lag error computed for T12
T25L	Sensing lag error computed for T25
T3L	Sensing lag error computed for T3
T4B	Turbine blade temperature for HP turbine
WFM	Fuel flow rate to main burner
WFR	Fuel flow rate to augmentor
ZNC	A generic term for any computed engine parameter which is to be compared with an observed parameter
ZND	Final values for cockpit display purposes (Fn, SMC, etc.)
ZSM	Stall margin modifier parameter representing engine deterioration assessment

TABLE A-2 - TYPICAL SENSOR REQUIREMENTS

	FUNCTION	ITEM	TOLERANCE *1 % of PT	SCALE RANGE FOR TOL.	MAX NORMAL	NO DAMAGE *2	EFFECTIVE TIME CONSTANT *3
1.	(ΔP/P)M3	PS3B	± 1.0	.14FS/FS	450 PSIA	500 PSIA	.0025
2.	Same	Pt3-Ps3	± 2.0	.10FS/FS	28 PSI	42	.002
3.	Fan PR	PS12	± 1.0	.1FS/FS	25 PSIA	38	.002
4.	Fan PR	PS14	± 1.0	.1FS/FS	46 PSIA	70	.0015
5.	Po	Po	± 1.0	65K/OK	-----	-----	.05 Sec
6.	To	To	± .5	300°R/560°R	-----	-----	.5 Sec
7.	Mo	Mo	Tolerance Effects Not to Exceed Those for Po				.05 Sec
8.	PLA	PLA	± .75 Deg	20/130	130 Deg	-----	.01 Sec
9.	T12	T12	± .5	300°R/800°R	800°R	900°R	2.5 *4
10.	T3	T3	± .5	800°R/1600°R	1600°R	1800°R	1.5 *4
11.	T25	T25	± .5	450°R/900°R	900°R	1000°R	2.0 *4
12	Core Trend	P25	± 1.0	.1FS/FS	52	70	.0015
13.	Bleed	Ps3B-PB	± 1.0	.1FS/FS	100	100	.002
14.	Nf&Ng	Nf&Ng	± .2	.4FS/FS	-----	-----	.008/.02
15.	BF/BG	BF/BG	± .5 Deg	0/50 Deg	-----	-----	.004
16.	WFM	WFM	± 1.5	.18FS/FS	11000	15000	.03
17.	WFR	WFR	± 2.0	.05FS/FS	80000	100000	.03
18.	P49	P49	± 1.0	.15FS/FS	115	125	.01
19.	P56	P56	± 1.0	.15FS/FS	45	50	.01

*4 Effective lag may be as large as 6X given if it is precisely controlled and computer compensated
*2 Accuracy in normal range not affected
*1 Two - Sigma basis - includes A/D conversion
*3 Combined lag of sensor and pneumatic line where applicable

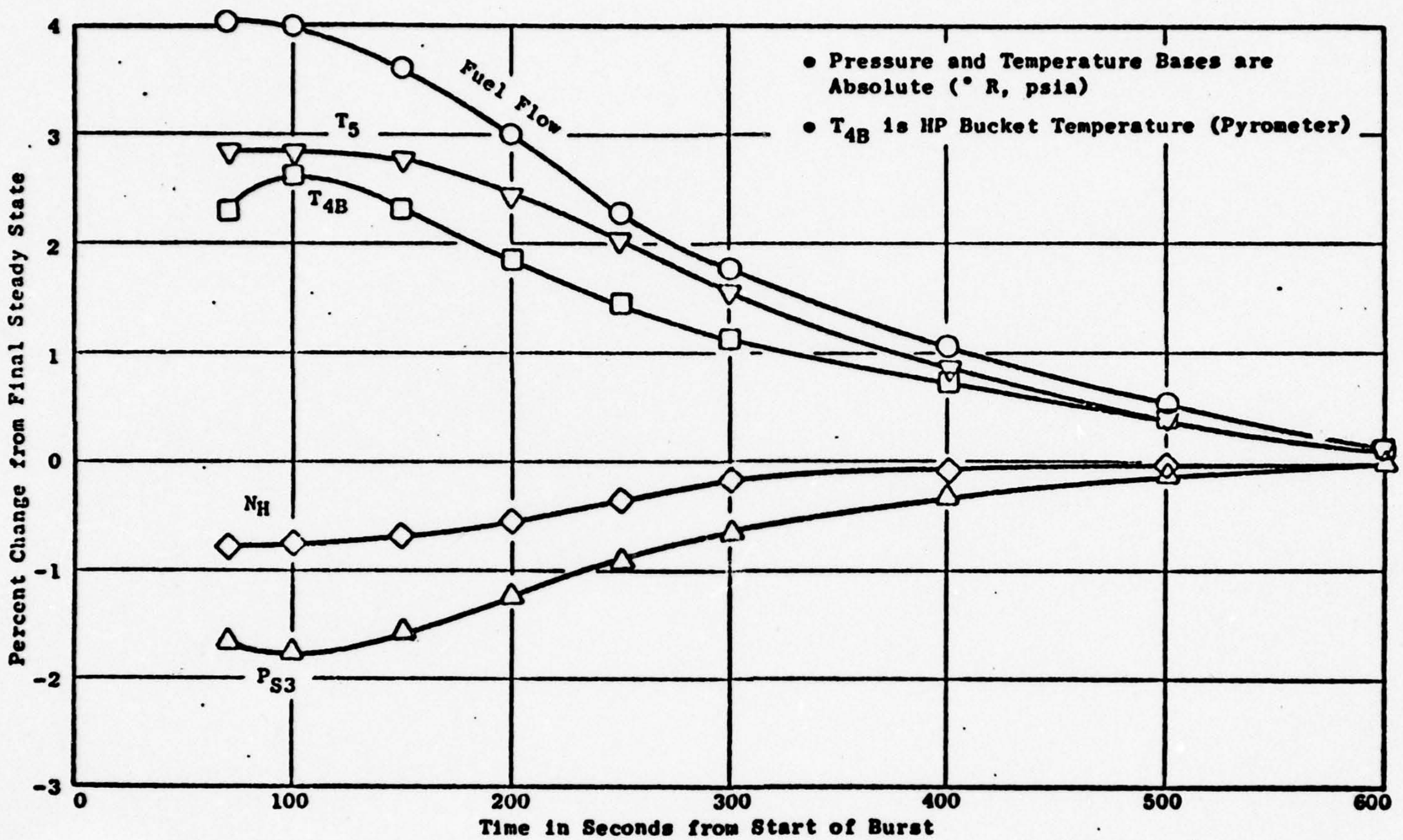

Figure A-1 F101 Thermal Soak Transient SLS Throttle Burst - Idle to 61° (Cold Rotor), Fan Speed (N_L), and Fan Discharge $\Delta P/P$ were Constant ($t \geqq 20$).

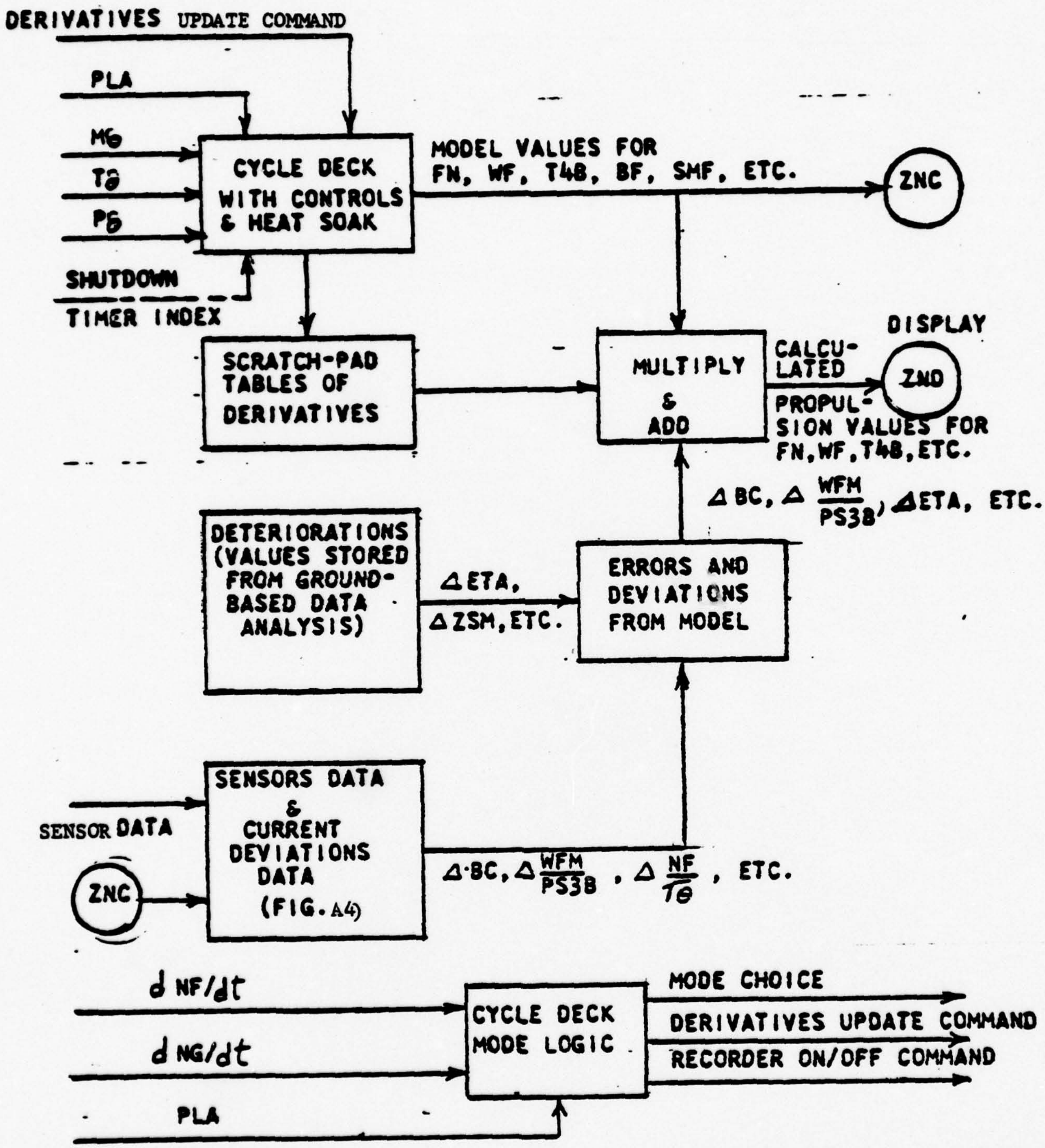

FIGURE A-2 - TCM SYSTEM FOR THE QUASI-STEADYSTATE MODE

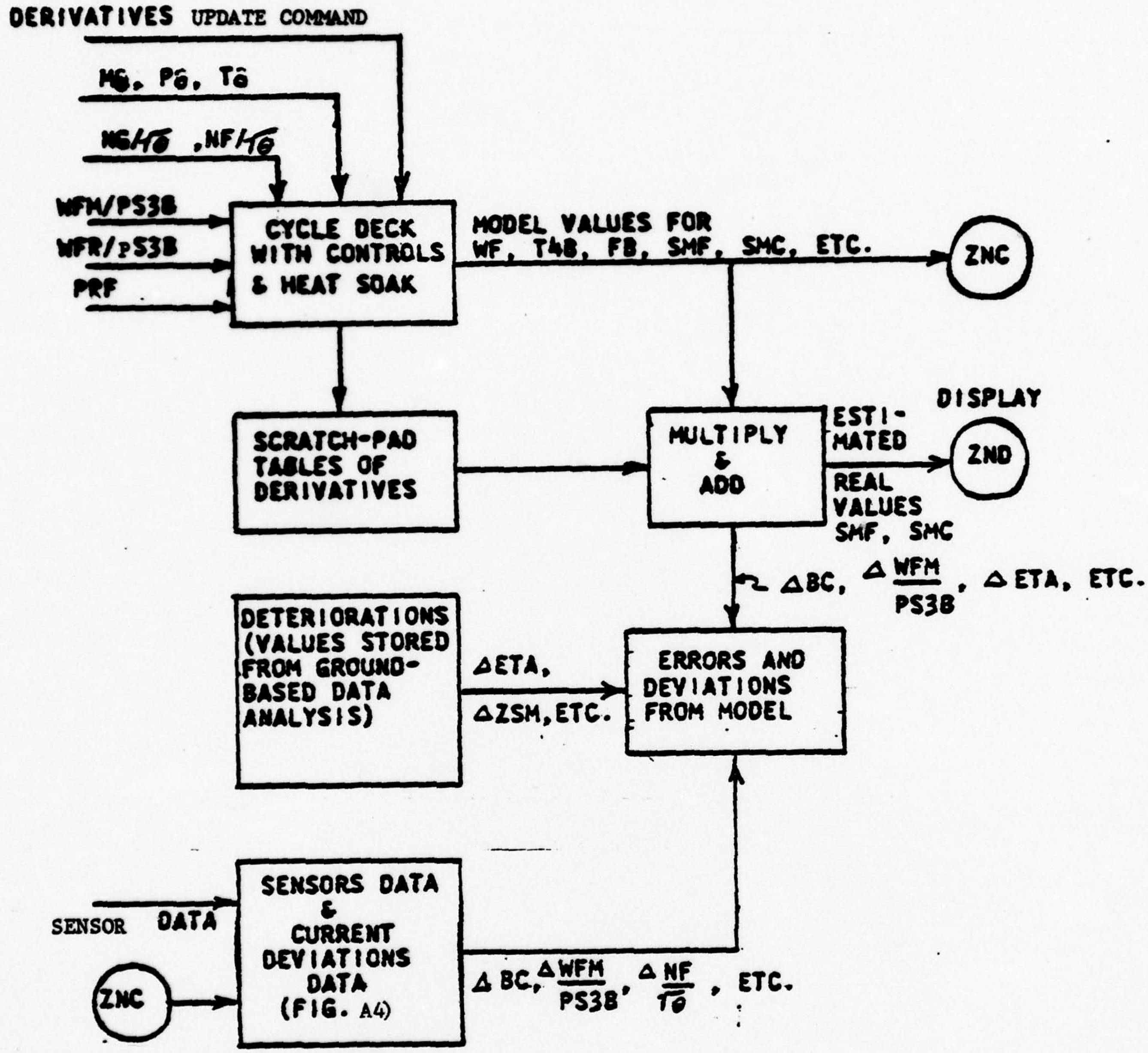

FIGURE A-3 - TCM SYSTEM FOR THE TRANSIENT MODE

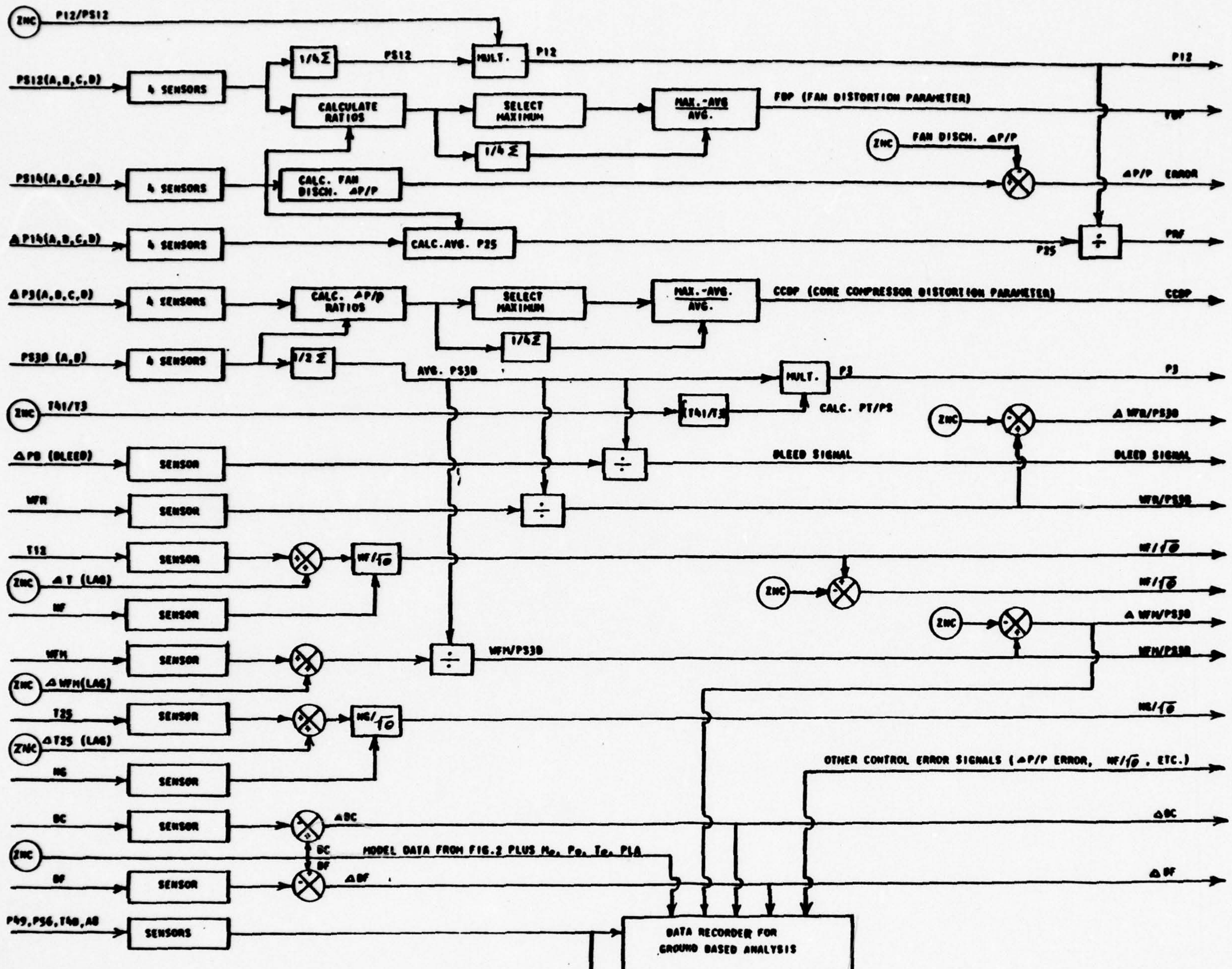

FIG.A-4 SENSORS DATA AND CURRENT DEVIATIONS DATA

APPENDIX B

INTEGRATED ENGINE INSTRUMENTATION SYSTEM -

IMPROVEMENT STUDY BASED ON STEADY STATE CONDITION MONITORING EXPERIENCE

INTEGRATED ENGINE INSTRUMENT SYSTEM -

IMPROVEMENT STUDY BASED ON STEADY STATE CONDITION MONITORING EXPERIENCE

1.0 INTRODUCTION

Previous Integrated Engine Instrumentation System (IEIS) study phases have addressed such topics as the necessary measurements, airborne computer logic, airborne data recording for (later) central computer processing, and in-flight displays. This improvement study was undertaken to determine if related new condition monitoring program techniques should be incorporated in the IEIS effort.

2.0 CONCLUSIONS

1. For aerothermodynamic monitoring, no reduction in size of the Phase III airborne software can be made using techniques found satisfactory in a related condition monitoring program.

2. For the lubrication/fuel monitoring systems a reduction in size of the Phase III airborne software can be expected using techniques found satisfactory in a related condition monitoring program.

3. The Phase III gross thrust meter availability assumption is no longer appropriate since no work has been undertaken to make it realistic. An alternate approach to obtaining this data is required.

3.0 RECOMMENDATIONS

1. Studies should be undertaken to reduce the size of the necessary airborne aero-thermodynamic logic significantly below that of the Phase III IEIS study and tailor it to the candidate engine.

2. Studies should be undertaken to establish the extent to which the lubrication/fuel airborne software size can be reduced and tailored to the IEIS candidate engine.

3. New instrumentation system feasibility studies and development work should be initiated in the next phase of IEIS. These should address replacement of the sensors that are currently immersed in the gas stream and expediting the development of an acceptable oil monitor.

4.0 AERO-THERMODYNAMIC MODEL IMPROVEMENTS

A feasibility study was undertaken to determine if simplified equivalent gas constants could be used instead of characteristic gas variables. This was considered worthwhile for the following reasons:

- The use of such constants could possibly allow a reduction in the size of the airborne aero-thermodynamic airborne software used as a base reference for real time monitoring.

- Studies have shown that errors less than ± ½% in combustor exit temperature would result in the use of such gas constants in the LM2500 CAPMS program at NAVSEC (Ref. Contract #N000-24-74-5193) where the engine will be operated at sea level static conditions and monitored in real time.

In a simplified approach, the most important calculation involves the combustor energy balance. One method is to calculate the combustor exit conditions as a function of the inlet conditions and the energy added. Findings show that the IEIS engine did not lend itself to such a simplified approach because the altitudes and Mach numbers at which the IEIS candidate engine must operate would introduce errors greater than ±2% in combustor exit temperature. However, further studies would probably not reveal approaches for use in airborne calculations that would permit significant reductions in the airborne software. The next phase of the IEIS effort should address such a reduction and estimate an acceptable size for the airborne software.

5.0 LUBRICATION MODEL IMPROVEMENTS

The lube model used in Phase III was for a development engine, and as such, included a great amount of logic that would not be necessary for a production engine such as the IEIS candidate.

A reasonable production type lube/fuel model would assess the following:

- Lube temperature as a function of fuel inlet temperature
- Lube pressure as a function of core speed and lube temperature
- Lube consumption as a function of time at specified core speed levels
- Rate of change of lube system debris

The assessment of the above four parameters will be required airborne software logic because they provide information about which the pilot can (and should) take preventative action. This model is currently estimated to be about 10% of the size of the Phase III Lube Model which was about 10,000 words. The next IEIS phase should evaluate this lube assessment model in depth and establish a better size estimate.

6.0 INSTRUMENTATION DEVELOPMENT

Sensors immersed in a gas flow passage have the disadvantage of being subject to breaking and having the fragments damage the downstream components. Overcoming this disadvantage is easy by designing a sensor so rugged that the probability of it breaking is negligible. However, a rugged sensor is apt to provide poor information because of a poor thermocouple time constant and blockage of the gas passage.

A specific effort must be initiated during the next phase of IEIS, with a goal of developing flight qualified sensors for use in gas passages by the early 80's when design of the IEIS engine will be started. Nonimmersion type sensors should be considered for this purpose. They would be mounted on the outside of the wall of a gas passage with only a small wall hole used to measure gas characteristics. At the present time, such a small wall hole can be used to measure static pressure providing adequate care is taken with the hole configuration and transducer connection.

TABLE B-1

NONIMMERSION TYPE SENSORS

MEASURED GAS PARAMETER	TECHNIQUE	USE
Gas Velocity	Laser Tracking	Calculate the difference between total and static temperature
Density	Radioactive Absorption	Calculate static temperature
Sonic Velocity	Acoustic	Calculate static temperature

Since the static temperature can be calculated from density and sonic velocity measurements, a feasibility study should be undertaken to establish which one technique will be developed to the flight qualified level.

A satisfactory oil monitor for detecting debris has yet to be developed. Work of this nature is currently underway in AEG by the Evendale Condition Monitoring Engineering Unit. However, the effort should be expedited in future IEIS phases to insure the availability of a flight qualified oil monitor by the early 80's.

Current work underway on a vibration monitoring system is adequate to expect this equipment to be fully flight qualified by the early 80's.

A gross thrust meter was assumed in the Phase III effort for the IEIS engine. However, no effort has been undertaken to indicate that this is now a realistic assumption for that time frame; therefore, no further use of a gross thrust meter should be considered and some alternate approach initiated.

7.0 THE IEIS CONCEPT

The IEIS objective is an improved airborne display that is computer controlled. This final goal is a good one. However, before achievement, extensive effort must be devoted to parameter measurement since the (display) output can be no better than the (parameter) input.

In the Phase I activity, the candidate engine was assumed to have an electronic control. Present indications are that the control will be of the "Full Authority Digital Engine Control" (FADEC) type. Data acquisition for IEIS purposes will then be simplified considerably, since this type of control normally will process all intelligence required except possibly vibration and lube system data. However, if signals defining these parameters were provided to the control, the processing of this data is feasible. The result would be digital output of all signals required for gas path and mechanical condition monitoring. In any event, isolation type circuits would be used at the controls/condition monitoring interface and no interference would be possible.

The Phase IV IEIS report indicated the need for a smaller size airborne computer program than was projected in Phase III. However, the current Phase V studies involving Transient Condition Monitoring could result in a need for a larger size airborne computer program. Thus, the projected size of the airborne software package for the IEIS engine of the 80's seems to be a variable. This variation could be controlled (to a degree) by firm adherence to guidelines as the following:

- The airborne computer/display system will be designed to provide the pilot only that information about which he can take corrective or preventative action. Such selected displays will be automatic, if a limit is exceeded, and on command, if desired.

- The airborne computer/recorder system will be designed to obtain information that will be processed by a general purpose off aircraft computer for individual engine maintenance and fleet logistics needs.

APPENDIX C

DISPLAY ENGINEERING

DISPLAY ENGINEERING

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Display Engineering

1.0 Introduction

The display engineering effort for Phase V of the IEIS Program provided the continued development of display formats and the evaluation of these formats by Navy pilots. This display effort was a continuation of the human engineering activity that had been conducted during previous IEIS Program Phases.

1.1 Human Factors Review

The human factors efforts during earlier program phases identified the pilot's engine information needs and the formatting of this information into usable display formats. Once these formats were established, an evaluation effort was conducted to obtain Navy pilot opinions regarding the merits of IEIS display concepts and the display formats. Phases III and IV were the first such evaluations. These efforts were conducted on the IEIS display itself, no other displays were shown and no attempt was made to simulate the cockpit environment. The purpose of these efforts was to evaluate, by pilot opinion, the concept and formats as they existed at that particular time.

The display concept and formats received overall pilot acceptance. In addition, pilots' recommendations provided inputs needed in order to pursue an orderly phase to phase development of the display formats.

1.2 Phase V Objectives

The human factors efforts for Phase V were a continuation of the evaluation of the IEIS display concept and formats. This evaluation effort made use of a static cockpit simulator and incorporated other associated cockpit displays. This was the first time the IEIS display formats were evaluated in a simulated cockpit environment. The purpose of the evaluation was to obtain pilot opinion regarding the display concept and formats; and to provide direction for format modification and expansion. These goals were accomplished. The Phase V Evaluation indicated that the IEIS display concept is a good concept and is well received by pilots. The basic formats themselves are satisfactory. There are, however, several areas where additions and improvements can be made. The individual format critiques and recommendations are discussed in detail in later sections of this Appendix.

In order to prepare for the evaluation exercise, several other tasks needed to be accomplished. These tasks were the following:

- Generation of an Evaluation Plan
- Development of Human Factors Display Criteria
- Modification of the display formats
- Updating of the scenario

Each of these tasks was completed and is discussed in this Appendix.

2.0 Evaluation Plan

At the outset of Phase V, GEOS and NAVAIRDEVCEN human factors personnel met several times to duscuss the Phase V evaluation effort. The output of these discussions was an Evaluation Plan which was submitted to NAVAIRDEVCEN on July 25, 1975.

2.1 Initial Evaluation Plan

This plan, as submitted originally, is contained in Appendix C1. Basically it called for a "Static" simulation exercise using the NAVAIRDEVCEN human factors cockpit simulator. All displays were to be generated by means of 35mm slides. Two scenario sets, one monochromatic and the other color, would be constructed. The pilot subjects were to observe the displays and would respond verbally to any commands. Two evaluators would record subject responses and comments during this exercise.

Each subject was to be given a familiarization presentation of the various formats and then would be run through a narrated scenario exercise.

At the completion of the exercise each subject was to be asked to complete a prepared questionnaire.

2.2 Plan Modification

As the various elements of the evaluation exercise were developed several modifications to the original plan were made. The evaluation exercise, as it was actually conducted, is discussed in Sections 6.0 and 7.0 of this Appendix. The major modifications are noted as follows:

- Pilot responses included simulated control actions as well as verbal responses.
- Only the color scenario was used
- A comparative evaluation was added
- Data recording was by evaluator/observer only - no questionnaire was used
- The evaluation exercise consisted of three parts rather than two

The basic goals and philosophy of the evaluation as established by the original plan were maintained and were carried through to completion.

3.0 Display Criteria

The human factors/display engineering function has been concerned with display criteria throughout all the IEIS Program Phases. An early task for Phase V was to define and develop, as necessary, those human factors display criteria that would apply to a cockpit display.

Criteria Definition

There is much data available regarding human factors criteria for airborne displays and our approach has been to review these data and tabulate those criteria applicable to the IEIS Display, this tabulation is shown in Table C-1.

Also for the Phase V evaluation scenario a color code was established as follows:

Green - Normal Condition and basic display color

Red - Critical Condition

Yellow- Marginal Condition

Orange- Instructional and checklist data

Most of the Table C-1 criteria could not be evaluated during Phase V because a slide presentation was used rather than a CRT. The actual evaluation and further development of criteria should be undertaken as separate tasks in a future Program Phase.

TABLE C-1 DISPLAY CRITERIA

BRIGHTNESS	300 FT. LAMBERTS (MIN.)
CONTRAST RATIO	2:1*(MIN.) @ 10,000 FT.-CDLS.
LUMINANCE RATIO	2:1 (DISPLAY:SURROUND)
REFRESH RATE	50 HZ
RESOLUTION:	
ALPHA-NUMERICS	10 - 12 SCAN LINES/CHARACTER
CHARACTER:	
HEIGHT	3/16 MIN.
ASPECT RATIO	5:7 WIDTH TO HEIGHT
STROKE WIDTH	(1/6 TO 1/10) X HEIGHT
FONT	LEROY (MIL-M-18012)
SPACING (BETWEEN LINES)	3/16 MIN.
ORIENTATION	VERTICAL

$$\text{*CONSTAST RATIO} = \frac{L_1 - L_2}{L_2}$$

WHERE L_1 = LUMINESCE OF SYMBOL

L_2 = LUMINESCE OF BACKGROUND

$L_1 > L_2$

4.0 Display Format Modification

The IEIS format development has been an iterative process through all previous program phases and has continued into Phase V.

4.1 Modification Rationale

The IEIS Phase V formats were a major modification from formats of previous phases. These modifications were necessary to incorporate recommendations from Phase IV, to add new formats, to add a color code, and to accommodate the display size reduction from 8" x 10" to 4" x 5". The display size reduction was necessary to make the IEIS formats compatible with both the AIDS and the human factors cockpit simulators at NAVAIRDEVCEN. Also the reduced display size is probably closer to what the actual size will be for cockpit applications.

The size reduction was the overriding consideration and it resulted in the wholesale modifications of all formats, all of which had undergone an orderly development over the previous program phases. In a sense the format development effort was starting all over again and the Phase V evaluation was the first exposure of these formats to pilot critique.

4.2 Format Elements

Each format is made up of basic elements, many of which are similar to elements of previous phases. The following is a discussion of the basic elements that make up the Phase V formats.

Status Bar

The Status Bar concept is carried over from previous efforts. The present configuration was that of a two segment bar shown in Figure C-1. The solid green bar indicates satisfactory engine performance and is continuously displayed.

If either engine malfunctions, the appropriate status bar segment will drop out and the respective "ENG 1" or "ENG 2" will turn red.

Vertical Scale Data

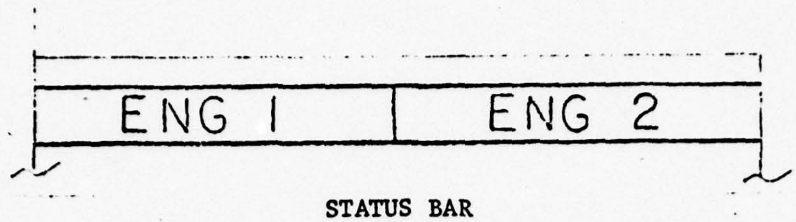
Vertical scale information is presented for either "RPM" or "THRUST", as illustrated in Figures C-2 and C-3. One of these datum is continuously displayed depending on the current flight mode. This display is all green except for the orange command carets and the orange bar graph. The command caret indicates the command setting by the point of the angle and the allowable range by the span of the legs of the angle. The caret is only displayed when a "go-to" command is required. This go-to command could be pilot or computer generated.

Horizontal Bar Graphs

Malfunction information is presented by means of horizontal bar graphs as was done during previous phases. The only modification is that the parameter title is on the left for ENG 1 and on the right for ENG 2. The complete bar graph and title is appropriately color coded. Figure C-4 depicts marginal and normal conditions and Figure C-5 depicts critical and marginal conditions.

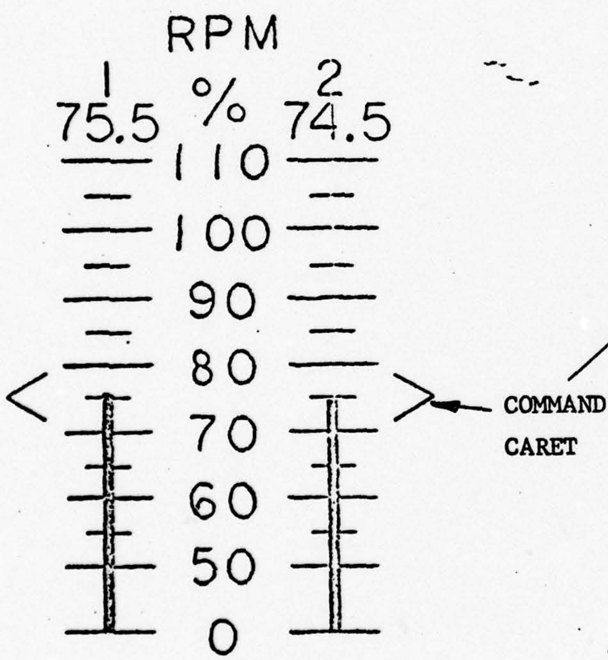
Instructional and Checklist Data

Corrective actions, commands, computer diagnosis, and checklist data are color coded orange and are presented in standard alpha-numeric formats, Figure C-6. As soon as the appropriate action has been completed, as sensed by the computer, the command or instruction will drop out.



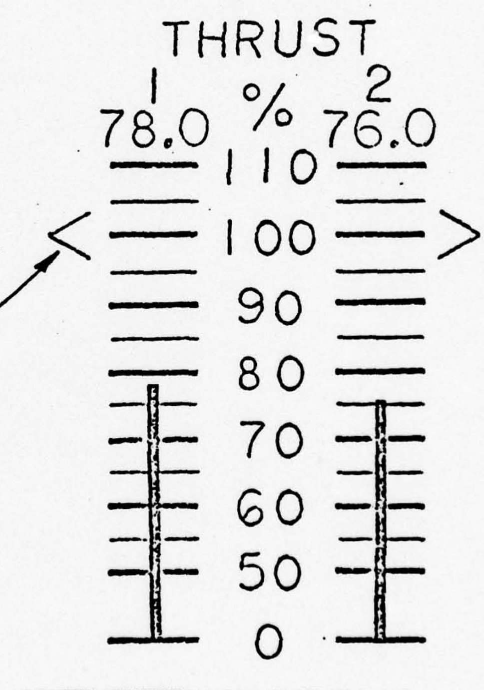
STATUS BAR

FIGURE C-1



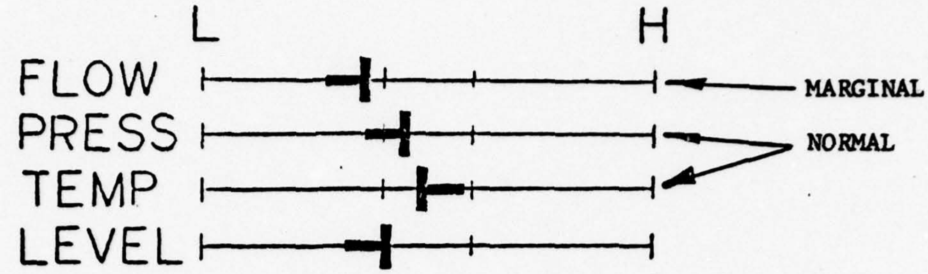
RPM SCALE

FIGURE C-2



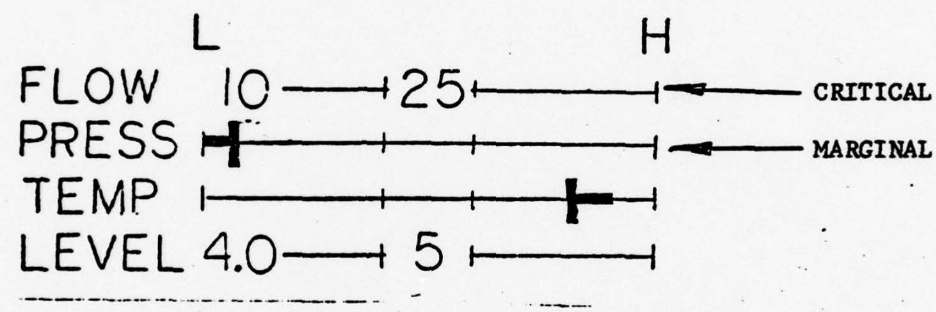
THRUST SCALE

FIGURE C-3



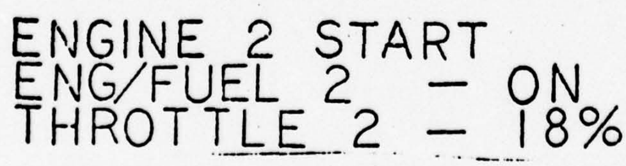
MARGINAL BAR GRAPH DISPLAY

FIGURE C-4



CRITICAL BAR GRAPH DISPLAY

FIGURE C-5



INSTRUCTIONAL DATA DISPLAY

FIGURE C-6

Energy Management Data

Climb and Cruise summary profile plots are illustrated in Figures C-7 and C-8. These are intended to be summary displays only and are not fly-to. These elements are the same as defined in Phase IV. They are reduced in size to fit the new display. Cruise Data, Range or Endurance, is available in tabular form, Figure C-9, at pilot request. Their numeric values will continue to change as the mission progresses.

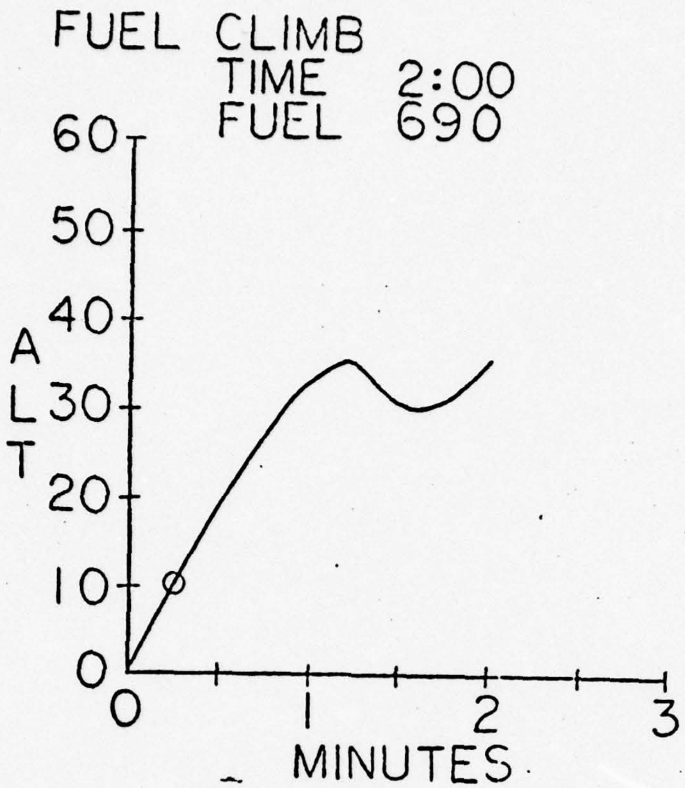
Pictorial Display

A pictorial display technique was introduced in the Phase V formats. This made use of a "triangle" to display thrust information to the pilot. Initially two right triangles were presented, one for each engine. As thrust began to build up, the triangles grew into a single isosceles triangle. This indicated that the desired thrust had been achieved. The pictorial data was supplemented by digital information which tracked the increasing thrust. Figure C-10 depicts the triangle display and a complete discussion of it is found in the evaluation results.

In addition to the above, other display elements were used. These were special cases such as airstart and weapon status and are self explanatory. Complete discussions of these display elements are included in the evaluation discussion.

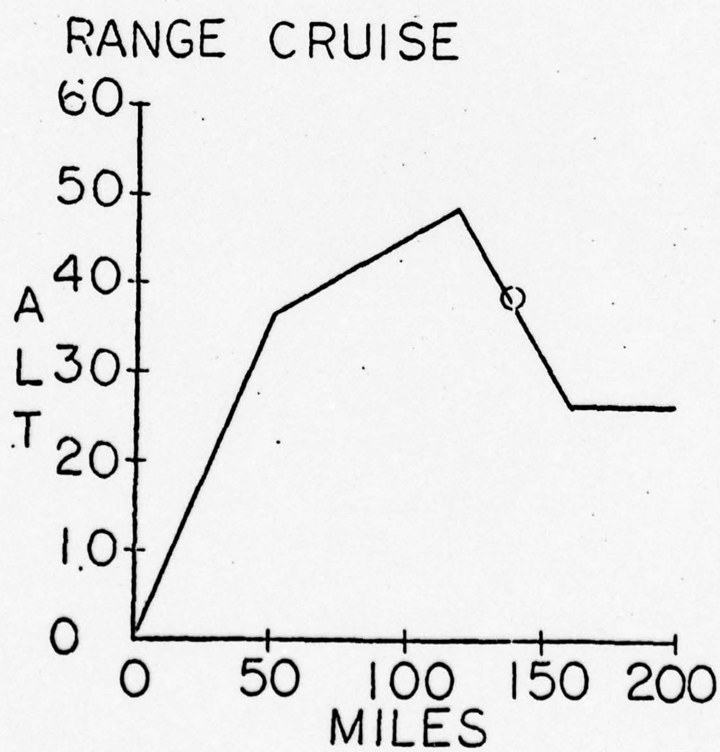
5.0 Scenario Update

The original intent of this task for Phase V was to update the existing Phase IV scenario. However, with the decision to use 35 mm slides for display presentation, rather than the IEIS demonstrator, a whole new scenario was required.



ENERGY MANAGEMENT CLIMB

FIGURE C-7



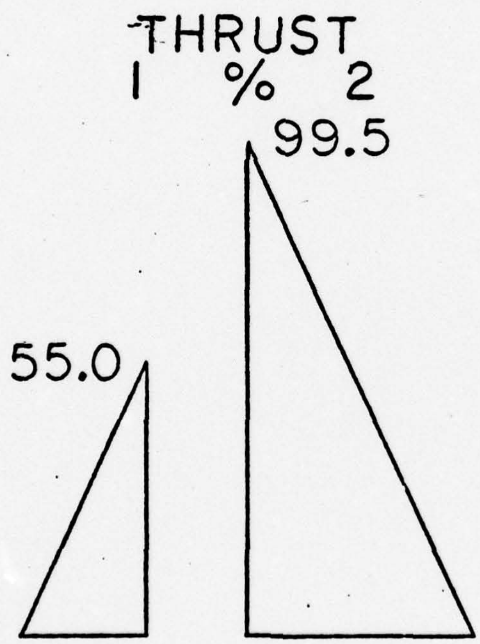
ENERGY MANAGEMENT CRUISE

FIGURE C-8

RANGE CRUISE
PRES 130 MIN 500 MI
MAX 155 MIN 570 MI

RANGE DATA DISPLAY

FIGURE C-9



PICTORIAL (TRIANGLE) DISPLAY

FIGURE C-10

5.1 Scenario Development

The mission scenario was developed from a U.S. Navy flight profile relevant to the capabilities of the A-6 aircraft. This particular profile was selected to demonstrate and evaluate the displays through a "typical" U.S. Navy mission.

6.0 Simulation Evaluation

The Phase V evaluation was conducted at the NADC Warminster cockpit simulator during the week of April 5, 1976. One at a time, subjects were received, seated in the cockpit and administered an interactive, dynamic simulation of the Phase V IEIS displays.

Subjects were instructed in the use of the simulator, performed a simulated flight mission, and were then asked to compare three unique display formats.

The average trial lasted 1.5 hours. Throughout, subjects were encouraged to air their criticisms and opinions of the displays. They also performed control functions required for the mission and responded verbally to a series of structured questions. Their actions were monitored for timeliness and accuracy.

Four rear projection screens were arranged on the front panel of the cockpit to simulate the Vertical Situation Display (VSD), Horizontal Situation Display (HSD), Master Monitor Display (MMD), and IEIS presentation. A total of 126 different slides were shown on the IEIS screen, throughout thirteen different flight sequences. VSD, HSD and MMD sample slides were shown at various times during each sequence to demonstrate the type of information and format available elsewhere in the cockpit.

6.1 Simulator Facility

A detailed description of the cockpit simulator used in this study is presented in the report, An Apparatus for Evaluating Pilot Preference of Electronic Display Information and Formats, NADC-76195-40.

The simulator was located at NADC Warminster and was both constructed and operated by NADC personnel. It depicted a single seat aircraft cockpit complete with instrument panel, stick and engine controls. The instrument panel contained four rear projection screens arranged to simulate the AIDS display concept. A Kodak Ektagraphic RA-960 Projector was positioned behind each screen to rear project 35mm slides of various display formats. Each projector was operated from its Remote Random-Access Control Panel to provide speed and flexibility in the selection of slides.

Indicated engine control feedback was provided when the Simulator Operator sequenced slides. Tactile feedback was provided by the control itself.

The simulator was located in an approximately 80 foot candles ambient light environment. No auditory, out-the-window vision or motion cueing of flight dynamics was simulated.

6.2 Subject Selection

Experienced pilots with U.S. Navy or U.S. Marine Corps affiliation were chosen as subjects for the study. They were selected not so much for their length of service as for their diversity in both aircraft flown and previous duty assignments. It was desired to have personnel who were acquainted with all aspects of U.S. Navy aircraft operations so that they might reflect back on possible advantages or disadvantages to each given display.

Further, it was intended to have a variety in the age of subjects so that display criticism due to attitude, training or conditioning might be revealed. Flying time for the group averaged approximately 2500 hours. Their experience included but was not limited to A-1, A-4, A-7, F-4, F-8, F-9, F-14, P-3, S-2, T-2, T-28, T-34, and light commercial aircraft.

The significant contribution of each subject is greatly appreciated. All acquired an enthusiastic interest in the study and were instrumental in providing the essential critique.

6.3 Trial Administration

Each trial was administered in five parts. The first trial was preceded by a rehearsal trial. No more than three trials were conducted in any one day.

The following personnel participated as trial administrators:

a. Narrator - W. Doerle, GEOS

b. Data Recorder - R. Cooper, GEOS

c. Simulator Operator - W. Breitmaier, NADC

d. Observer/Data Recorder - J. Polin, NADC

Part 1, Introduction, consisted of welcoming the subject, briefing him on the purpose of the study, and explaining what was expected of him. Data collected included the subject's vital information, experience and his impression of the overall study and display concept.

Part 2, Slow-Walk-Through and Explanation (semi-interactive), consisted of a step by step explanation of each display by the Narrator until

he felt confident that the subject was familiar with it. Data collected included learning characteristics, a comparison with other aircraft systems, and subjects' initial observations and criticisms.

Part III, Half-Speed Simulation (totally interactive), consisted of the simulated flight mission. Data collected included responses to structured questions; subjects' observations, criticisms and recommendations.

Part IV, Format Comparison - color and monochrome, consisted of a preference comparison between three display formats. Data collected included responses to structured questions; subjects' observations, criticisms, and recommendations.

Part V, Debriefing, was a review discussion and subjective analysis conducted only among the evaluators at the end of each trial.

6.4 Data Collection and Analysis

Throughout each trial, data was collected in five ways -

a) Audio tape recording on six 120 minute cassettes

b) Hand written account of all of the subject's actions and comments - Data Recorder

c) Handwritten subject responses to all structured questions- Data Recorder

d) Handwritten highlights of each trial - Narrator

e) Summary discussion - Narrator, Data Recorder, and Simulator Operator

One subject voluntarily submitted written comments and recommendations following his trial.

The analysis was conducted by categorizing comments, criticisms, opinions and recommendations according to the sequence in which they occurred. From this it was possible to pinpoint problem areas, whether in a particular display or transition between displays. The findings are presented in Sections 7.1 and 7.2.

Structured questions which compared a particular display to a pilot's "own" aircraft were weighted by the Data Recorder to indicate degree of preference. These comparisons were categorized and are presented in Section 7.3.

Criticism of the three thrust formats was derived primarily from structured questions, although obvious problems and assets were voiced throughout the entire trial. Thrust format criticisms, likewise, were compiled and categorized. They are discussed in Section 7.4.

7.0 Results and Discussion

The results of this study are presented in the order in which they were observed and analyzed. A brief synopsis of the subjects' criticisms and opinions as well as the rationale for some aspects of the display design are discussed.

7.1 Slow-Walk-Through and Explanation (Part II)

During the Slow-Walk-Through and Explanation part of the trial, each subject was shown displays representative of the type he would be viewing during the actual evaluation. As the displays were presented one-by-one the Narrator explained their format and operation to the subject. He detailed the type of information which is found on each display, how it changes, where the computer commands appear, and how his actions would be indicated. In most cases, only one or two slides from each display needed to be shown to the subject before he felt relatively familiar with it.

In general, subjects' initial reaction to the displays was passive. Where time permitted, subjects performed the required control actions. Many actions occurred as a function of what subjects anticipated as well as what they were told. These were recorded and analyzed to assure that the System design capitalizes upon natural control responses as well as preconceived characteristics of familiar equipment. Because some subjects never got to operate the controls until Part III, initial control performance is discussed in that section of the report.

All subjects readily accepted the color coding which was demonstrated. One subject initially thought the caret, rather than the tape, indicated actual values. Subjects questioned the lack of an 18% position on the throttle. They were also concerned with the unrealistic start procedure of the scenario. Subjects stated that RPM probably would increase to some moderate value <u>before</u> the throttle was moved.

Shape and orientation of the caret probably elicited more initial comments than any other display component. Subjects were unsure of its real purpose. Even after its use was explained to them, subjects agreed the indication was probably not as effective as it might be. They pointed out that orientation of the caret depends upon which information is more crucial, the exact commanded value or the operating tolerances. Some suggested that the caret should be reoriented to point toward the scale.

Although most of the pilots were accustomed to engine instruments and engine controls on the left side, only two of the subjects commented on the lack of control/indicator co-location with this engine display on the right.

In several instances, subjects became preoccupied with apprehensions over system reliability, effectiveness of existing hardware and the ability of the system to sense all variables. Subjects were also concerned over the logistics of inputting and changing computer data. They asked many and varied questions about the displays which are characteristic of the learning process. Subjects were markedly attentive, very involved, and deliberate in both verbal responses and operation of controls. Initial exposure to the displays revealed no major deficiencies in either the concept or familiarization with the System.

7.2 Half-Speed Simulation (Part III)

In this phase of the trial, subjects were instructed by the Test Director to start up the engines, initiate takeoff, select various mode options, perform emergency procedures, and land the aircraft. The subject was required to perform all interactive control functions and respond verbally after they were completed. Following each sequence of displays, the subject was asked a series of structured questions to elicit his opinions and design recommendations.

The mission consisted of fifteen such sequences, all of which were representative of what a pilot might experience during an actual tactical mission. The sequences were programmed as follows:

a.) Self-Test

b.) Engine 1 Start - Malfunction

c.) Engine 1 Start - Shutdown

d.) Engines 1 and 2 Start through Takeoff

e.) Fuel Climb

f.) Trim Thrust to 100%

g.) Range Cruise Plot

h.) Range Cruise Data

i.) Air-to-Ground Attack

j.) Air-to-Air Attack

k.) Engine 1 Malfunction - Immediate Response

l.) Airstart Engine 1

m.) Engine 1 Malfunction - Delayed Response

n.) Landing

o.) Secure Engines 1 and 2

Obviously, some of these sequences contained transitions from one type of display to another. The study was primarily concerned with information and formating of each display*, but also with the compatibility and integration of information during the transition.

In all, there were a total of thirteen different displays presented within the fifteen sequences of the mission. Some were only variations of basic formats, but all were unique enough to catagorize them separately for analysis. The displays used in the simulation were as follows:

a.) SELF-TEST

b.) ENGINE START (0-50% RPM)

c.) FALSE START

d.) RPM (0-110% RPM)

e.) THRUST (0-110% THRUST)

f.) ENGINE MALFUNCTION

g.) FUEL CLIMB

h.) RANGE CRUISE PLOT

i.) RANGE CRUISE DATA

j.) AIRSTART

k.) AIR-TO-GROUND/AIR-TO-AIR ATTACK

l.) LANDING

m.) SECURE ENGINES

*"Display" will be used to refer to display formats.

In the remainder of this section, the design, operation and usefulness of each display will be discussed on an individual basis. Likewise, the display's effectiveness relative to the particular sequence in which it was used and its compatibility with other displays will be analyzed.

7.2.1 SELF-TEST

The Self-test Display as illustrated in Figures C-11 and C-12 received very few comments. Subjects voiced more concern over the ability of the system to check itself and provide adequate diagnostics. Subjects agreed, however, that the pilot would have little use for diagnostics. Several subjects questioned the purpose of displaying "PASS" three times, but "FAIL" only once. They acknowledged that if the intent was to display a screen test, the screen should be flooded or a test pattern presented. Perhaps an "all-color" background with black "TEST PASS" would be appropriate. Subjects agreed there should be an obvious difference between the pass and fail indications and that instructions on what to do about a failed test should be provided.

If the self-test process is of an obvious duration, a "self-test in progress" indication should also be displayed.

7.2.2 ENGINE START (0-50% RPM)

The Engine Start Display is a modified RPM Display with a scale of from zero to 50 percent RPM (Figure C-13). It appeared when the subject depressed his ENG 1 START actuator.

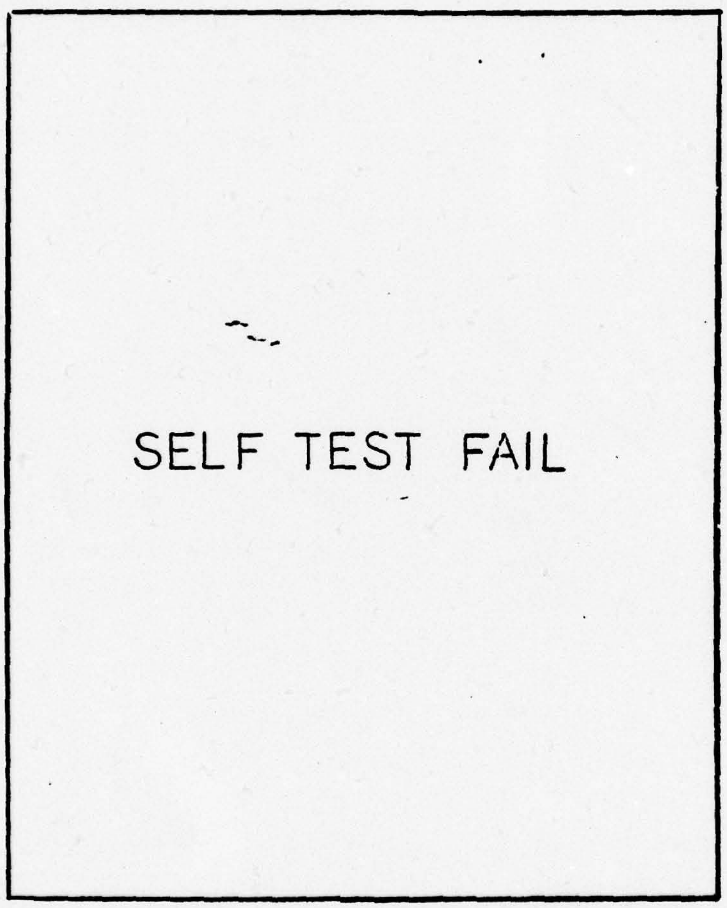


FIGURE C-11 SELF TEST DISPLAY (FAIL)

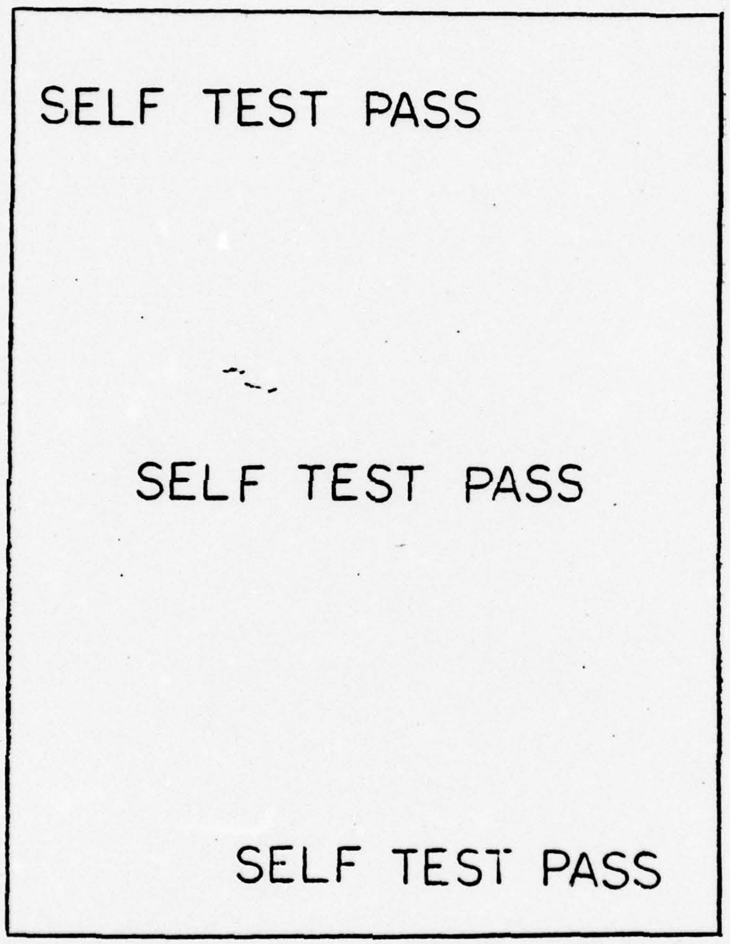


FIGURE C-12 SELF TEST DISPLAY (PASS)

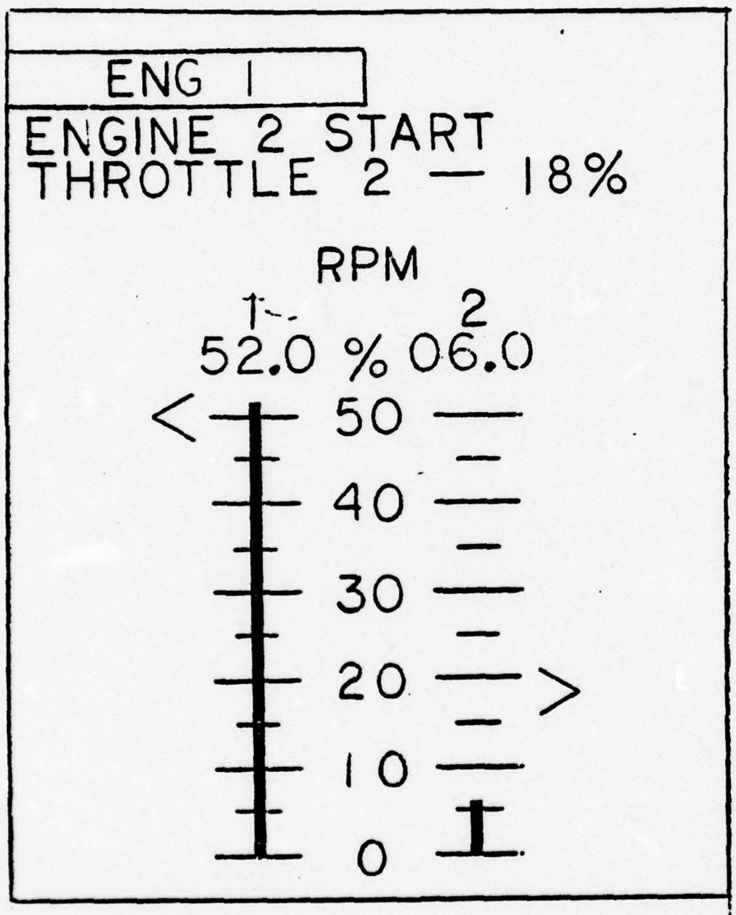


FIGURE C-13 ENGINE START DISPLAY

Subjects responded favorably to the Engine Start Display, but were intensely critical of the Start Sequence. Their complaint was well founded. It was based on the simulation's lack of complexity which is found in the start-up procedure of today's aircraft. Subjects cited, for example, that they would not operate the throttle until RPM adequate for "light-off" had been achieved. Further, they stated that the actual checklist is much more extensive than the simulated checklist, and that the actual throttle settings would be more by "feel" and experience than by specified position.

The consensus among many subjects was that throttle position commands should be eliminated. Where specific power settings are required, the parameter (eg. RPM, thrust, fuel flow, etc.) rather than the throttle position should be addressed. One subject suggested that throttle position might be indicated on the display along with the actual and commanded values. Another subject stated that he had witnessed such a display and that the feature was probably not worth the additional display complexity. An indication of "IDLE", "INTERMEDIATE", and "MIL" on the scale, might be helpful.

A major concern of all subjects was the display's inability to indicate engine "light-off". Subjects acknowledged that this would be a very anxious period for the pilot particularly in the absence of fuel flow information. One subject suggested that the tape or caret might flash until "light off" has occurred.

A few subjects expressed the desire to monitor parameters such as fuel flow and temperature during start-up. They stated that engines respond differently each time they are started and the pilot wants to see this difference. Subjects admitted under questioning that a pilot does very little with this information and would probably not need it if he was confident of the System's ability to give him a safe start.

One statement questioned the need to continue displaying ENG 1 START after the engine had started; another questioned the usefulness of so many scale numbers.

The Engine Start Display also appeared in the Engine 1 Start-Shutdown Sequence. In this sequence Engine 1 was arbitrarily secured by the pilot even before it had achieved idle. The intent was to demonstrate to the subjects how the System would respond when overridden by the human element.

When instructed by the Test Director to shut down Engine 1, subjects responded very quickly. In most cases, the ENG/FUEL SWITCH was switched off by the subject without referring to the display. The written command, however, served as a checklist item. Most subjects followed the tape as RPM decreased rather than the digital readout. Some subjects expressed concern that in a real dynamic display, the digital readout numbers would be changing too fast to be read.

One subject found the upper portion of the vertical scale confusing and too cluttered. Several subjects suggested that once the throttle is returned to OFF, the carets should return to zero and "ENG 1 START", disappear.

In general, the concept of the Engine Start Display was well accepted. It must be noted, however, that this particular sequence was brief and occurred early in the simulation. Due to design similarities, Some criticism of subsequent RPM displays may also pertain to the Engine Start Display.

7.2.3 FALSE START

The Engine 1 Start-Malfunction Sequence was not totally representative of an actual "false start" (Figure C-14). Subjects were quick to point this out. They did acknowledge, however, that there are several types of start malfunctions and that all could be presented on this display with great benefit to the pilot. Subjects stated that some start malfunctions are difficult to analyze and once determined are handled very differently. The written and symbolic commands of the false start display would ensure the proper procedure for each start problem. Subjects agreed that if the System deemed a shut-down appropriate, the pilot could be so informed.

Subjects were unhappy with the loss of RPM values following the transition from Engine Start to a Malfunction Display. Several stated that this is when they want RPM information the most. They also had reservations about the way the Malfunction Display presented RPM values and what marginal (yellow) and critical (red) RPM really meant. Some subjects suggested presenting the vertical scale RPM Display but adding the alarm parameters when required. They cited examples in which one engine was running, but the second might not start. In this case they might want to throttle back the first engine.

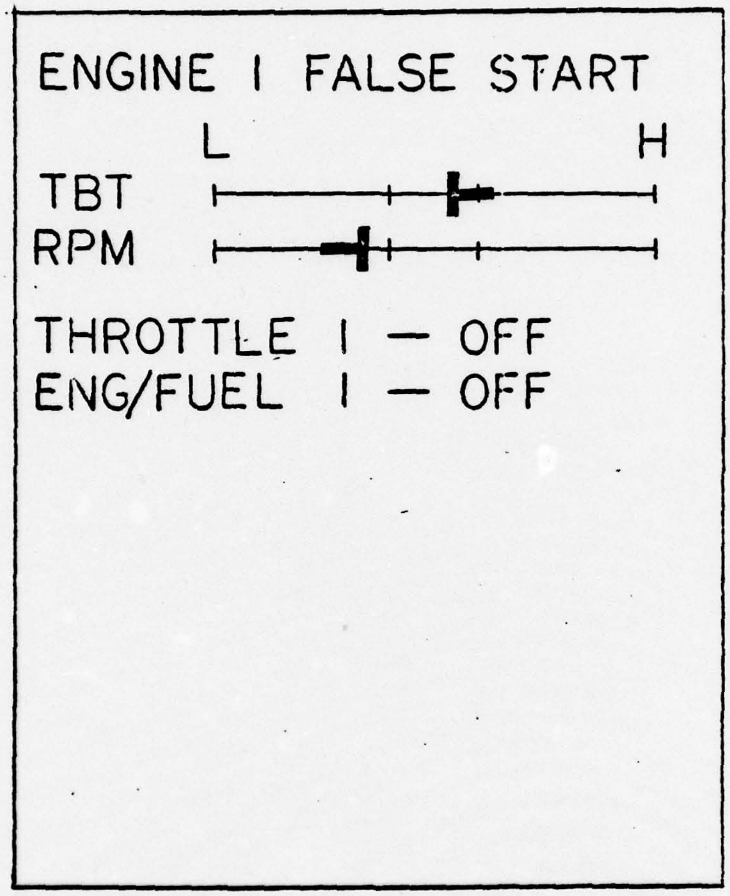


FIGURE C-14 FALSE START DISPLAY

In many cases, it was suggested that "ENG 1 START" be dropped if the engine malfunctioned or did not "light-off".

Some concern was also expressed over the pilot's inability to "see" fuel flow during a start malfunction. This apprehension was apparently more out of concern for safety than for management of consumables.

In general, subjects favored the concept of presenting both problem and solution. They agreed that written commands were good in this situation and that they could readily interpret from the display all that was required.

Practically every subject commented on the need to improve spacing between words and to increase the separation between the written commands and horizontal tapes. The need for vectors on each tic mark to to indicate trend or direction was questioned since movement should be obvious to the pilot.

The Engine 1 Start-Malfunction Sequence was brief and occurred early in the simulation. Due to design similarities some criticism of the Engine Malfunction Display may also pertain to the False Start Display.

7.2.4 RPM (0-110% RPM)

The RPM Display with a scale of from zero to 110 percent was presented after both engines had achieved idle (Figure C-15). Subjects made no comment whatsoever regarding the transition from a 0-50% to 0-110% scale and no detriment to operation as a result of the transition was observed.

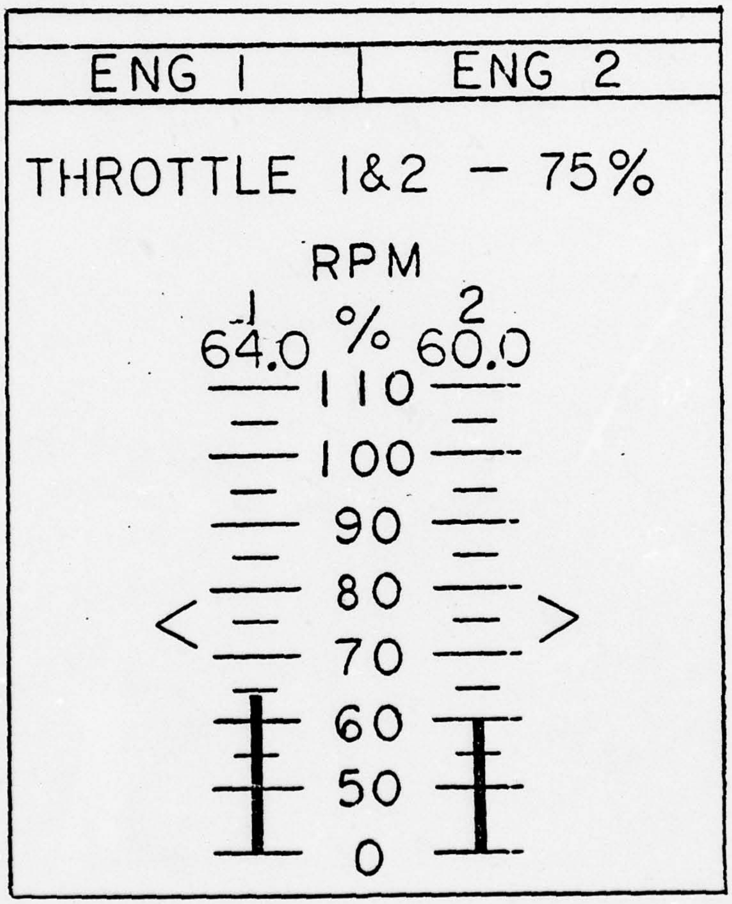


FIGURE C-15. RPM DISPLAY

The RPM Display was used in this simulation for taxiing, engine run-up, and landing. It was somewhat similar in format to those used in present day aircraft. Subjects are very familiar with RPM measurement and currently use it as an indicator of engine health and performance. As such, the vertical scale concept for presenting RPM information was readily accepted. Several subjects believed the location of this RPM Display to be far superior to its location on their present aircraft.

The orientation of the caret made it very difficult to use, particularly when exact settings were required. Subjects seldom used the digital readouts for setting RPM. They stated that the readouts caused the upper portion of the vertical scale to appear cluttered. They also pointed out that the digital readouts could not be read and, in fact, were occasionally mistaken for scale numbers. Viewers saw no need for the "1", "2", and "%" above the scale. Spacing and separation between words must be improved.

Subjects were probably most disturbed about the use of written and symbolic commands for RPM. They stated that a pilot should have complete freedom to "jocky" the throttle as he wished during taxiing, and engine run-up. During takeoff he would use maximum power under practically all conditions. Subjects foresaw no obvious use for the commanded RPM unless it was dictated by an engine check-out requirement or operating restriction. In this case commands would be valid. Again, there was a strong preference for written commands to reference RPM, not throttle setting.

During the taxi and run-up portion of the Start through Takeoff Sequence, several subjects expressed a desire for additional display information. Those still somewhat skeptical of the System's ability to monitor and report engine anomalies wanted fuel flow, temperature, and perhaps lubrication information. The majority of subjects, however, felt the status bar and RPM at this time was adequate. One subject suggested that time limitation information might be helfpul prior to takeoff. He stated pilots must be kept appraised of time constraints.

7.2.5 THRUST (0-110% THRUST)

Transition from the RPM Display to the Thrust Display occurred in the Engines 1 and 2 Start through Takeoff Sequence when the pilot selected TAKEOFF mode. The Thrust Display consisted of a zero to 110 percent thrust scale (Figure C-16). Graduation lines on the thrust scale were of variable thickness to differentiate it from the RPM scale of variable graduation line (see Figures C-2 anc C-3). This technique was unsatisfactory. In only two cases out of nine did the subjects recognize that the parameter they were monitoring had changed.

Subjects were relatively unfamiliar with the meaning of "thrust". Much of their discussion was preoccupied with how it is measured and its value to the pilot. One subject summed it up well. He remarked that at present he must interpret thrust from three different measured parameters. He would accept a value for thrust, but still wants the option to view any or all of the others.

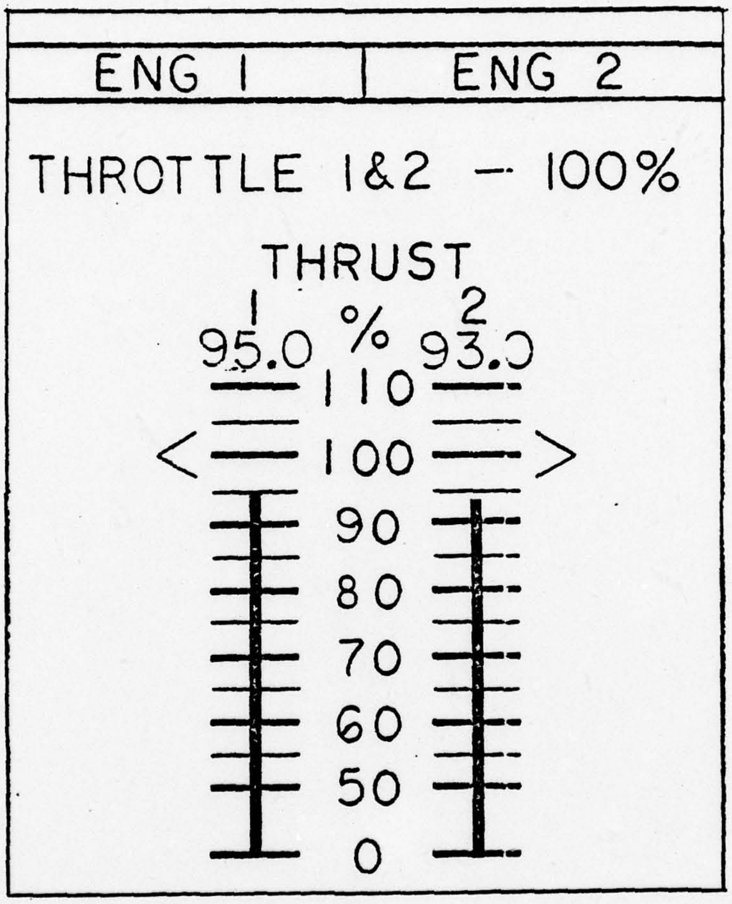


FIGURE C-16 THRUST DISPLAY

All subjects pointed out the advantage of reduced eye scan with a single engine display. They also expressed a view about power settings not previously heard.

When a pilot applies power to his engines, tactile feel and throttle position are probably his major source of immediate feedback. Occasionally there is a disproportionate relationship between throttle movement and display change. After awhile, however, the pilot learns this difference. If a Thrust Display is incorporated into the System, throttle control is bound to appear disproportionate.

One suggestion is to make the thrust scale non-linear since thrust increases rapidly toward the end of throttle travel. Another method, of course, would be to artificially compensate for the throttle movement.

Subjects agreed that takeoff was probably the best time to display thrust. Even then, however, a few would have preferred options to "call-up" fuel flow and temperatures. One subject suggested the pilot might want to revert back to the RPM Display during afterburner.

Because the Thrust Display is quite similar in format to the RPM Display, many of the previous shortcomings were again voiced. Caret orientation, location of the digital readout, inadequate separation between words, and the necessity for "1", "2" and "%" were questioned.

Subjects reemphasized the irrelevance of written throttle commands during takeoff and normal flight. Even if a data link is employed or if the aircraft must be flown at a specific thrust, the carets should be adequate for pilot response. One subject stated that if a pilot must rely upon written commands, then he is certainly "behind" his aircraft. Subjects were adamant that only checklist items which are generated for routine compliance should be displayed. Their presentation must be compatible in design with other checklists presented in the cockpit.

While increasing thrust to 100% for takeoff, subjects watched the tape movement rather than read the digital readouts. They explained that the tapes were excellent for deriving rate information while the digital readouts were best once thrust had stablized.

There was discussion about the need to indicate when actual thrust reached commanded thrust, or at least fell within the tolerances of commanded thrust. This feature certainly is within the capability of the System. Whether or not it is an appropriate parameter to display to the pilot should be the subject of further investigation.

Once at altitude, subjects were instructed to, "Trim Engines 1 and 2 for 100% thrust." The choice of words in the instruction and the task itself, although artificial, did elicit the desired responses.

Subjects were quick, deliberate and very confident in their actions. This particular sequence was relatively relaxed and gave the subjects opportunity not only to reflect back on what they had previously said, but to critique the Thrust Display in greater detail. Here, as probably in real flight, they became most aware of the display's usefulness.

When asked if they were confident of engine health simply by seeing the green status bar, opinions were generally tied to the subject's "trust" of the System. Some believed that the only way to acquire this "trust" was to see the real System and to fly it.

One subject felt even the green status bar was not necessary to convey "operations normal." Others wanted not only the bar, but the option to call up other parameters such as fuel flow and temperature.

When asked what <u>one</u> additional parameter beside thrust might be displayed, both fuel flow and temperature (ie. EGT, TIT and blade temperature) were chosen. Oil pressure, oil temperature, and time at engine temperature were also requested.

Again the consensus among most subjects during normal cruise, was the desire to monitor their consumables. Subjects questioned the need to display tenths of an RPM on the digital readout.

One individual pointed out that the lower portion of the vertical scale is meaningless once the tape has moved upward. He stated that his visual cue is between the top of the tape and the index graticule or caret.

This observation may be important since it was previously believed that relative and absolute tape lengths are a vital cue to reading the display. Significant design simplifications could be made to the display if this new finding is substantiated.

7.2.6 ENGINE MALFUNCTION

The Engine Malfunction display is presented whenever the System senses a marginal or critical condition in engine operation. When a marginal condition is presented, the display appears with at least one parameter displayed in yellow. If the pilot does not take immediate action and the condition deteriorates, the yellow parameter will go red and others probably appear yellow (Figure C-17)

To fully demonstrate this, two different sequences were simulated during the mission. The Immediate Action Sequence required subjects to respond as soon as they detected a malfunction. A Delayed Action Sequence was incorporated to show the subjects what they could expect if their action was severely delayed.

As the subjects observed the total operation of the Malfunction Display, they expressed their dissatisfaction with several things. First and probably most significant was the loss of all thrust or RPM information at a most critical time. Subjects were particularly disturbed to find they had lost the "good" engine's primary parameter, even though they might have to rely on it to get "home". Subjects were further disturbed over the displayed commands to secure the "bad" engine. They stated that much more is involved in a decision to secure engines than the engine requirement itself. They looked, instead for indicators to help them make this decision; such as time-to-turbine failure,

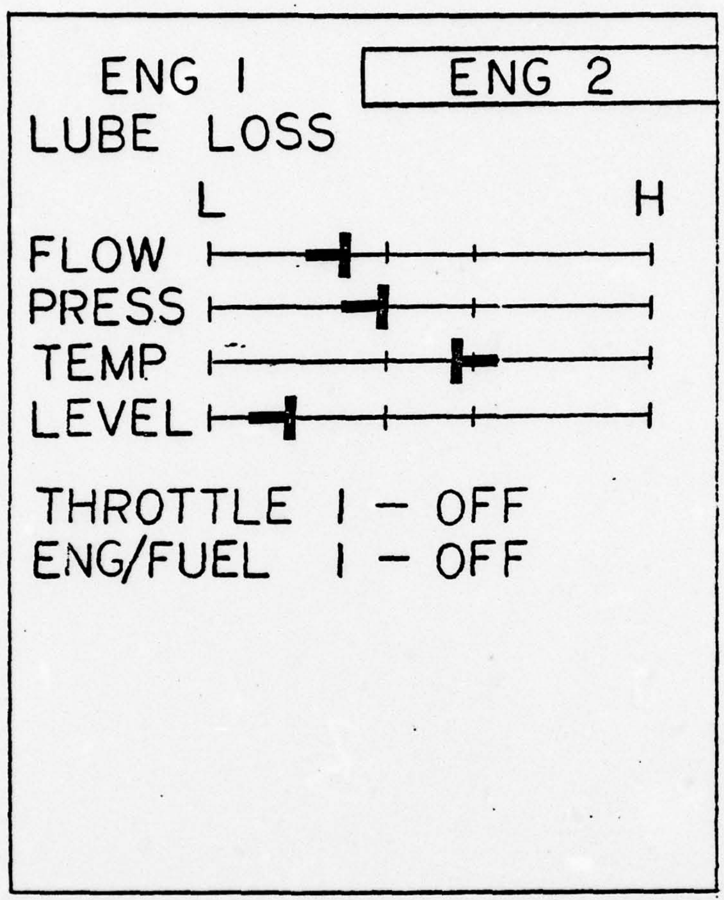


FIGURE C-17 ENGINE MALFUNCTION DISPLAY (MARGINAL)

probability of fire, etc. They also expressed the desire for options or recommendations on power settings for the "bad" engine. Anything short of shutting it down!

This information, the subjects believed, would be very beneficial to the pilot and would be the most effective use of the System. Subjects did acknowledge that if a turbine failed or fire occurred, the displayed checklist commands would be essential.

Several subjects questioned what the display would look like if the second engine went "down". They cautioned against developing a "too busy" display; but at the same time were grateful for presenting detailed parameters, trends, rates of change, actual and normal values and priorities. One subject remarked that if the System can give him all that, why doesn't it just tell him what is wrong and present him with options and consequences.

Subjects were obviously concerned over how the System would determine when to present the Malfunction Display. They cited the many fluctuations and irregularities in present engines, particularly as the many modifications. They were fearful not only of the display coming on unnecessarily, but also that System buffering (e.g. false alarm checks) may mask an irregular or borderline value.

Subjects did point out some obvious deficiencies with the display as they viewed it. "LUBE LOSS" appeared in red even though none of the parameters had gone critical. This was inconsistent with the coding. Subjects again noted inadequate separation and spacing of written material.

Once a parameter has reached the critical value with the tic mark off the scale, a digital readout of actual values appears on the scale along with the nominal value (Figure C-18).

Subjects were asked if these values would be of help to them in such a situation. Responses were divided. All individuals agreed that trends were more important than absolute numbers. Some stated they would know what the actual numbers meant; others that they would <u>not</u> and that there was no easy way to find out. Subjects also stated that they would determine the meaning of the value by comparing it to the nominal value , zero, or maximum.

It appeared as though all subjects were seeking trend information. Ironically, once a parameter had reached the critical stage, the only trend information available was from the digital values.

One subject requested to see the nominal and actual values even during a marginal condition. Another preferred to continue monitoring engine parameters after the engine was shut down. Further investigation into what motivated these comments is recommended.

Many advantages of the Malfunction Display were revealed during the course of the simulation. An engine malfunction was very easily detected because the entire display changed. Also, degradation of a parameter was very obvious both as the tic mark moved and color changed.

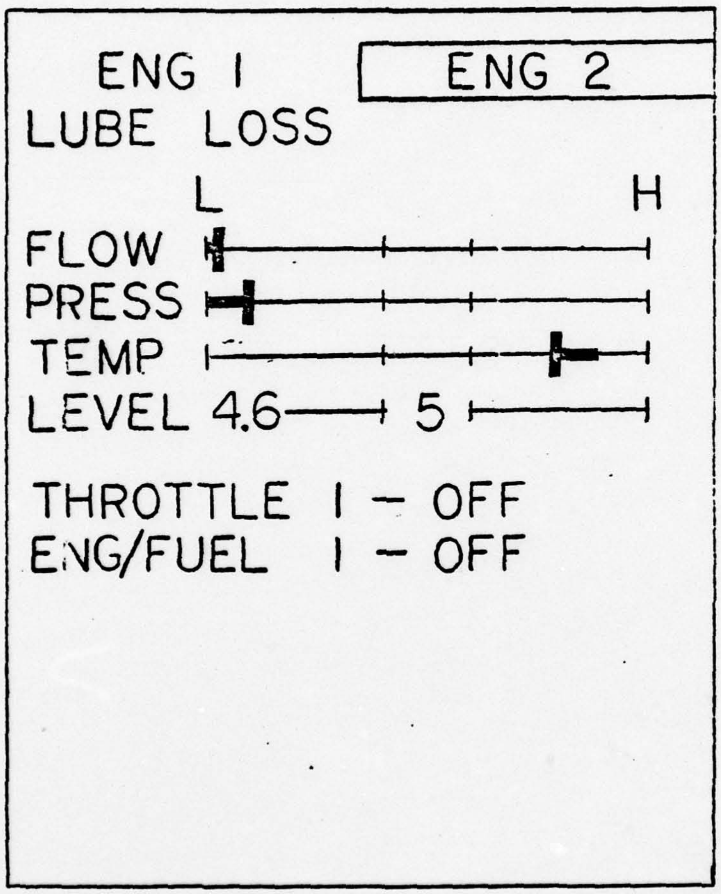


FIGURE C-18 ENGINE MALFUNCTION DISPLAY (CRITICAL)

Compared to present day aircraft, subjects found this display far superior to the "ladder" panel because it did not "take the pilot so far into the cockpit." Two subjects believed the display gave them earlier warning than their present indicators. They were pleased to see trends prior to criticality so that they could continue operation but had time to reevaluate their mission.

In general, the color coding and concept of the display was well received by the subjects. Format and information requirements should be reviewed to avoid complicating the pilot interface during these stressful periods.

7.2.7 FUEL CLIMB

Immediately upon lift-off, and assuming the FUEL CLIMB mode was selected, a transition from the Thrust Display to the Fuel Climb Display took place. This display is intended not as a "fly-to" indicator, but instead provides supplemental information (Figure C-19).

The concept was considered by subjects as most appropriate in fuel critical aircraft. It was also suggested for minimum time climbs, time and fuel descents, and even altitude changes. Most subjects stated that their HUD "fly-to" information was adequate to accomplish the task. They foresaw a much more valuable use for the System and display, as follows.

Optimization requirements of fuel, time, range, etc. are pretty well planned prior to takeoff or at least the pilot is aware of the aircraft's characteristics. Rutowski information is utilized and the flight parameters from takeoff to final altitude are known.

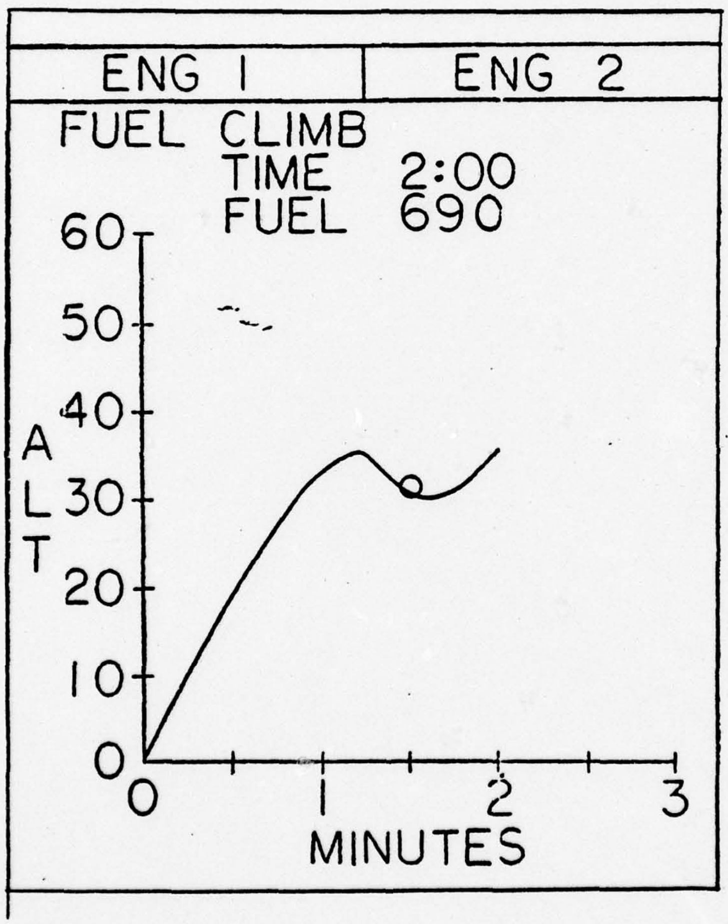


FIGURE C-19 FUEL CLIMB DISFLAY

AD-A035 566 GENERAL ELECTRIC CO WILMINGTON MASS AEROSPACE INSTRU--ETC F/G 21/5
INTEGRATED ENGINE INSTRUMENT SYSTEM. VOLUME II.(U)
JUN 76 R L SKOVHOLT, W S LITTLE, W A DOERLE N62269-75-C-0359

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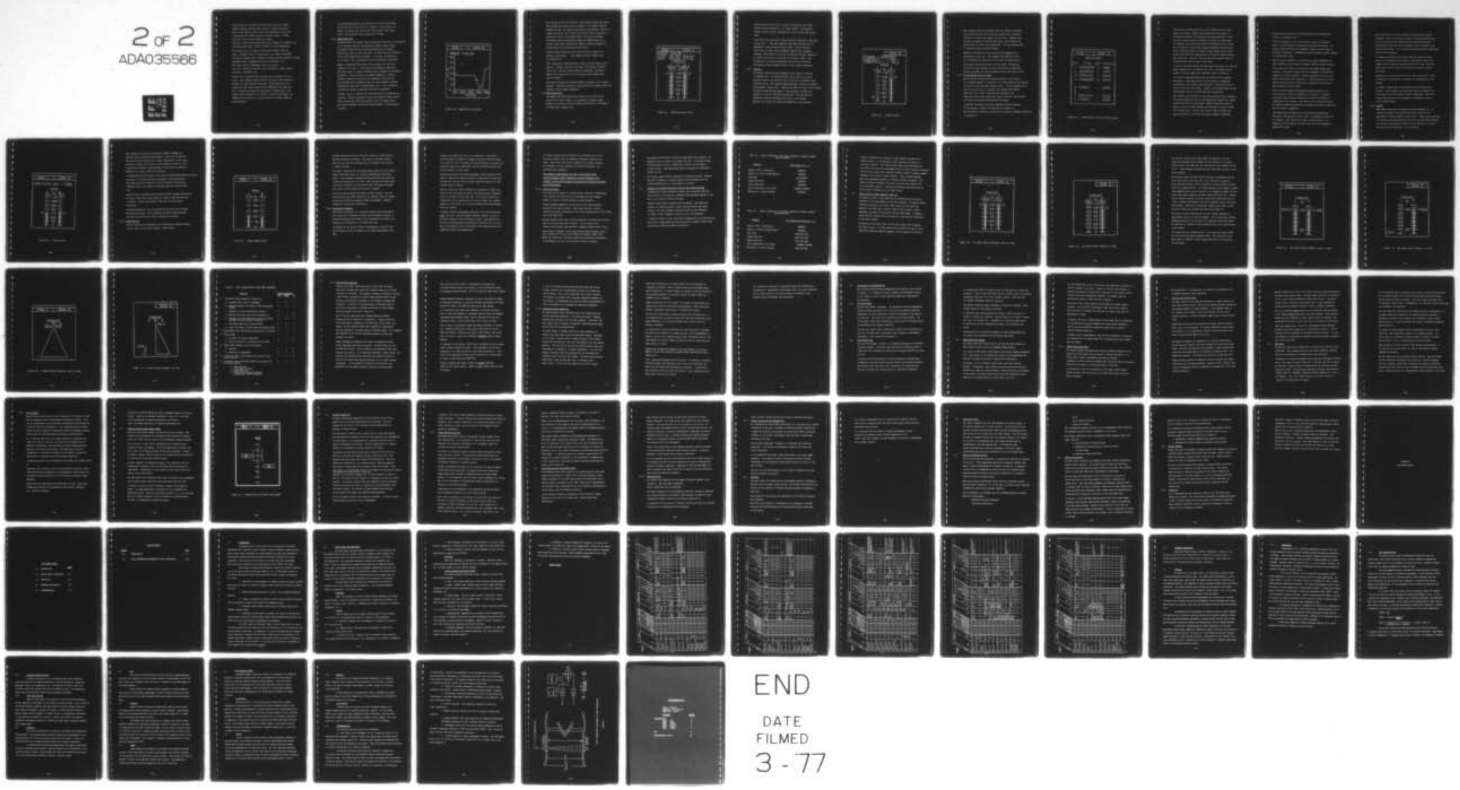


END
DATE
FILMED
3-77

Anytime after the aircraft has rolled into position for takeoff, however, factors effecting these curves can change drastically. Pilots would readily welcome a real time presentation of the fuel consumed and time elapsed, as well as optimal values. Further they would like to see the effects of traffic incidents, control center deviations, fuel consumption or transfer, and even malfunctions which effect the airfoil, on this optimization.

The subjects felt this display could be made "smarter" than the pilot. He should be able to input data on any number of variables and then be presented with a variety of options and their predicted outcome. Relatively static information such as was presented on the Fuel Climb Display is redundant and of little use to the pilot. Subjects all agreed a good interactive, dynamic display could be an invaluable tool.

Several minor complaints other than the lack of dynamics were discussed. Most subjects agreed that since this was a "fuel sensitive" display, full flow should be indicated. Subjects were also concerned over their loss of thrust values immediately following lift-off. At this time, pilots are very mindful of engine power. One subject found it difficult to "relate" to minutes on the graph. He suggested that altitude vs. fuel or altitude vs. distance might be more meaningful.

The overshadowing theme in the critique of the Fuel Climb Display was that Navy pilots are very fuel conscious. As one subject remarked, "We cannot land 'before' fuel and we cannot land 'after' fuel." They do believe this concept can be of help.

7.2.8 RANGE CRUISE PLOT

The Range Cruise Plot Display might be selected by the pilot in anticipation of an evolution which he was required to perform (Figure C-20). The flight profile would have been programmed prior to takeoff, would be the result of data link inputs, or would have been developed by the pilot himself while in flight. In any case, the display is not a "fly-to", but is intended to provide supplemental information.

Subjects acknowledged the purpose of this display, but were very doubtful of its value. If the display were designed primarily to give them actual vs. optimal information and a forecast of anticipated evolutions, then the display was somewhat inadequate. Subjects initially criticized the display for commanding evolutions but not revealing how to accomplish them (ie. power settings, altitude, required air speed, rate of climb/descent, etc.). This information is within the System's capability and should be presented.

Secondly, actual vs. optimal fuel values may have to be displayed continuously. Subjects expressed concern over losing the thrust values. They concluded that they would probably select the range cruise plot very infrequently and only for brief glimpses of what maneuver to expect.

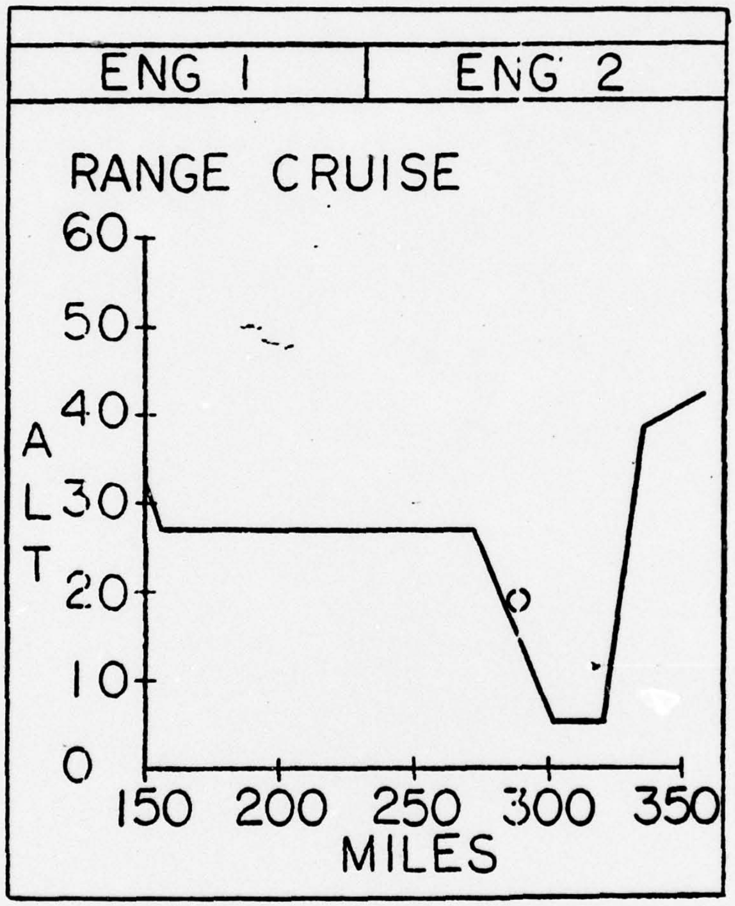


FIGURE C-20 RANGE CRUISE PLOT DISPLAY

This concept was not well received. Most subjects agreed they would have reviewed the profile prior to takeoff. If, however, inflight changes are made, the display would acquire a new meaning. When the flight plan varied, pilot or data link entries could be computed to provide the pilot with countless control options and solutions. The display would be particularly helpful in BINGO situation or during a "fuel light" approach and landing. Subjects conceded, it would probably not be monitored during attack.

Several subjects questioned the pilot's ability to operate the System in such fashion. They suggested further research into its practicality.

Other comments are worth mentioning. Scales were too large to be of much use. Subjects could only read them to the nearest 2,000 feet and 5 miles. The type of miles should be indicated. The scale might be more easily read if the line and/or "bug" changed color when "on target".

Two subjects objected to presenting flight information on an "engine display". They were particularly distressed about the Range Cruise Plot Display's lack of engine information.

7.2.9 RANGE CRUISE DATA

The Range Cruise Data Display was selectable by the pilot as an option to the "plot" display. It consisted of the basic thrust display plus written actual and optimal information for continuation of range cruise (Figure C-21).

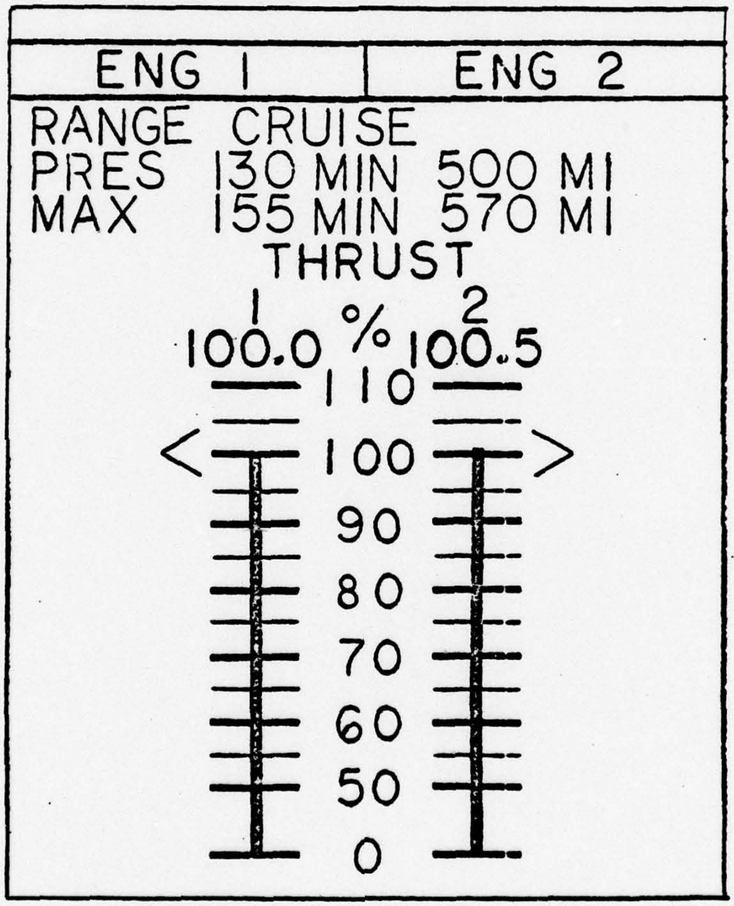


FIGURE C-21 RANGE CRUISE DATA DISPLAY

Subjects critical of the lack of engine information on the "plot" display were more receptive to the "data" display. Most agreed a composit display could be developed which would satisfy both requirements.

Along with thrust information, several subjects requested an indication of fuel flow. They also suggested that power settings could be commanded in order to maintain range cruise. Several subjects stated that the range cruise information might be more optimally arranged. They pointed out the lack of separation between components and reemphasized previous criticisms of the thrust format. From observations, all subjects apparently were willing to sacrifice anticipating flight information just to retain engine information.

7.2.10 AIRSTART

The Airstart Display appeared immediately upon subject's selection of AIRSTART mode. It's primary purpose was to serve as an engine airstart checklist and indicator while maintaining information on the operating engine. This display appeared somewhat similar to the Engine Start Display (Figure C-22). Because the number of items on the airstart checklist exceeded display space, it was necessary to present new commands once the old ones had been performed. This technique for presenting checklist information was unique to the Airstart Sequence, and as such was especially conspicuous to the subjects.

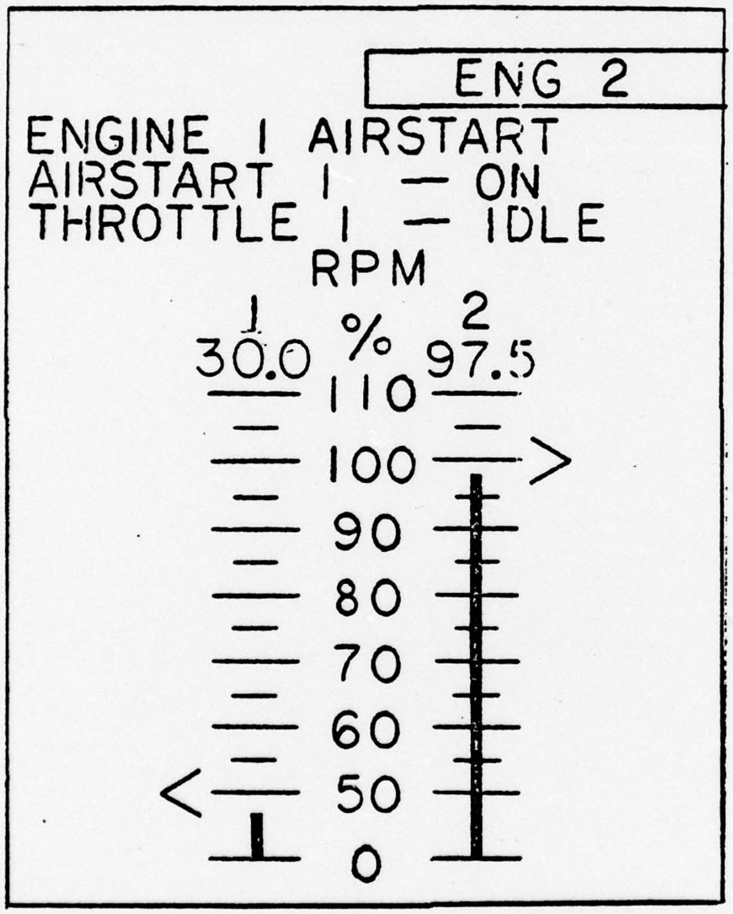


FIGURE C-22 AIRSTART DISPLAY

Many subjects expressed displeasure with the checklist technique. They stated they would like to see the complete list of actions required to re-start their engine or none at all. Subjects were divided over whether a checklist was useful. Some believed the display would be viewed only peripherally. All were explicit that it should not require detailed reading.

Subjects considered the lack of power setting commands to be appropriate at this time. They suggested the addition of fuel flow information and especially an indication of engine ignition.

The Airstart Display was found to be very useful, although the simulated Airstart Sequence was quite optimistically simplified. Subjects performed the Airstart Sequence quickly and without error.

7.2.11 AIR-TO-GROUND/AIR-TO-AIR ATTACK

The two Attack Sequences were performed using the same display. Air-to-ground weaponry is presented on the lower portion of the display; air-to-air on the upper half (Figure C-23). Type of armament and its status is written out on a vertical list complete with station number and color coding. Subjects were requested by the Narrator to select each attack mode, then to "act out" the selection and release of missiles as dictated by the display.

In general, the display was easily understood and well accepted by the subjects. A major criticism was the absence of detailed missile information considering the System's tremendous capability to present it.

ENG 1 | ENG 2

WEAPONS

STA	TYPE	QTY	STATUS
1	SIDEWNDR	2	ARM
2	SPARROW	1	SAFE
3	SPARROW	1	SAFE
4	SIDEWNDR	2	SAFE
5	SHRIKE	1	SAFE
6			
7	WALLEYE	1	SAFE
8	SHRIKE	1	SAFE

FIGURE C-23 AIR-TO-GROUND / AIR-TO-AIR ATTACK DISPLAY

Actual missile loading and firing is more complex than the attack sequence portrayed. Subjects were impressed with the amount of information presented. They suggested providing even more to help the pilot evaluate missile readiness and conduct the launch phase. For example, a pilot must know which of two missiles on one station he is activating. He must have fuzing information, receive missile modes, status and alarms, and monitor various phases of the launch. He must also know where missile packs are located and when they have been jettisoned. Above all, the pilot must be constantly aware of an armed missile and know when it has fired.

It was not determined exactly how much target information (eg. position, speed, heading, etc.) is needed by the pilot. One subject stated, however, that this might be an appropriate place to present it.

All subjects expressed opinions over the location of the armament information. While some favored the concentration of weaponary indications on one display, others believed it required the pilot to look too far "into" the cockpit. Subjects were concerned that missile controls would not be co-located with their indications.

Some subjects were desireous of continuous engine and fuel information. They were apprehensive over how the display would appear if an engine malfunction occurred during attack. Subjects emphasized that the degree to which an engine degrades may determine the pilot's "break-off" during attack. In this case, he would want to monitor his engine display and at the same time require armament information.

Subjects questioned the Air-to-Ground/Air-to-Air Attack Display's ability to accommodate this.

Further investigation of the attack display concept is warranted based on two contradictory statements by different individuals. One subject stated that when he is engaged in combat, he never looks at his engine instruments. Presumably he would be warned of engine failure on an annunciator light.

Another subject disagreed. He insisted that engine management and fuel information is particularly necessary during the attack maneuver.

Criticisms of the format and operation of the attack display were numerous. Most subjects agreed that the arrangement of material was adequate but could be improved. Several questioned the need to show missile names rather than designations. Subjects assured us of their familiarity with missile designations and emphasized the ease with which designation could be read.

Several subjects suggested arranging the display similar to the actual physical location of armament on the aircraft. In effect, the display might become pictorial with a greater utilization of symbology and color coding. Such a format would eliminate the need for station numbers and might make the display both easier to interpret and less "busy" in appearance.

Some terminology and coding used on the display was misleading. According to the subjects, missile "safe" is understood and need not be indicated. Also, use of red to show an armed missile is inconsistent with the code and "release" would be a more appropriate command than "fire".

Due to the absence of missile controls on the simulator, display arrangement could not be control oriented. Subjects questioned why air to air missiles were displayed during air-to-ground attack. Another stated there was really no reason to show all missiles once one had been selected. All of these particulars should be investigated prior to further design.

Of paramount interest to the subjects was their control of each missile on a multiple missile station. They wanted to know, for example, how to select one particular missile in a pod. They also stated they could not detect if and when one of the two missiles had fired.

Subjects were curious to know how the display would appear if they had selected a wrong missile as opposed to an alternate but valid missile.

In general, subjects were very pleased with the concept of the display. They believed a new pilot could learn to interpret this presentation much faster than his present indications. Their only strong objection was to the inadequacy of information on such a "busy" looking display.

7.2.12 LANDING

The landing display was initiated by selecting LANDING mode. It looked very similar to the 0-110% RPM display, except for the appearance of landing commands (Figure C-24). Under normal conditions the Landing Display would probably transition from the Thrust Display. In this case, discrimination between the two would have to be much more obvious than experienced in the simulation.

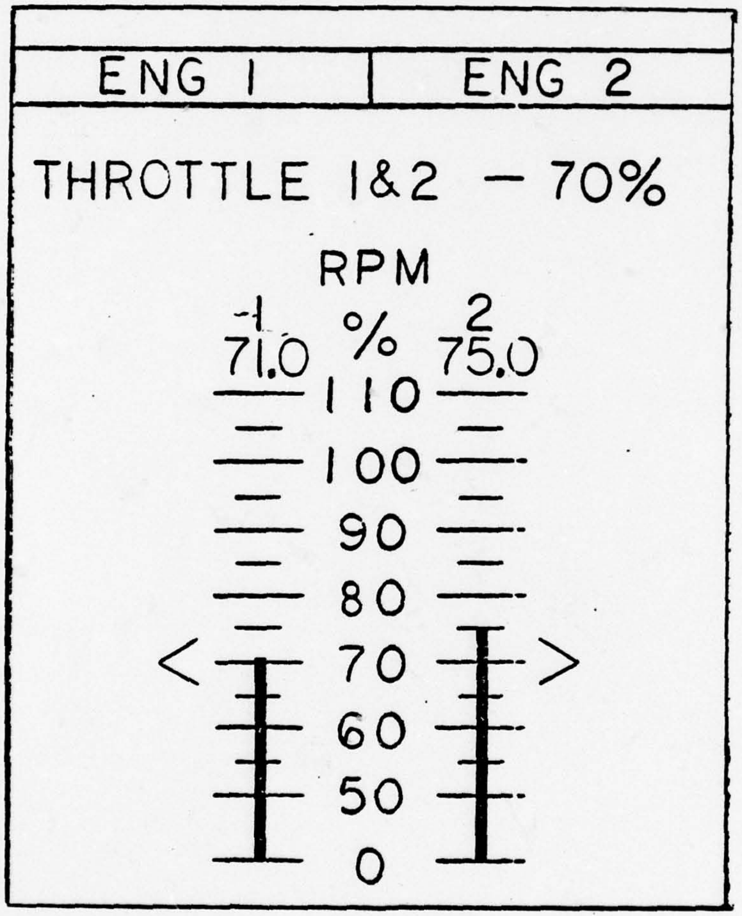


FIGURE C-24 LANDING DISPLAY

Most subjects objected to the written and symbolic commands for specific throttle settings during landing. They cited the need for each pilot to have free control of power, particularly at this stage. He could, of course, have elected a fuel optimization mode or be constrained by an automatic landing system; in which case, at least the symbology (ie. carets) would have remained.

As expressed during the Engines 1 and 2 Start through Takeoff Sequence, subjects were eager to see more check-list information. One subject stated that engine checklist information could be presented on the Landing Display as long as its format was compatible with the aircraft checklist.

Several subjects questioned why the Landing Display indicated RPM instead of thrust, particularly since takeoff and normal cruise was conducted in "thrust". Perhaps this change to RPM should not occur until "touch-down".

One obvious deficiency of the simulation was the absence of a Letdown and Approach Sequence. This intermediate evolution might have made the transition from normal cruise to landing more coherent.

7.2.13 SECURE ENGINES

Once the landing was accomplished, the Test Director instructed subjects to taxi, park, and then secure engines (Figure C-25).

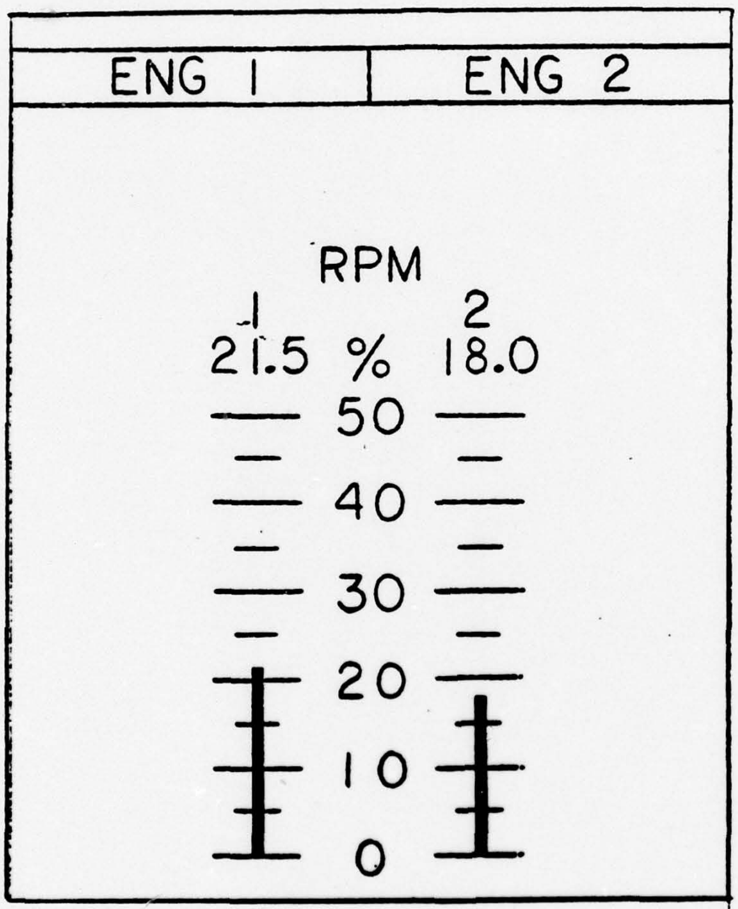


FIGURE C-25 SECURE ENGINES DISPLAY

Subjects implied that engine indications would be of little value to them while taxiing and parking. They were quick to add, however, that the usual shut down procedure was quite extensive and required a lengthy checklist.

One subject suggested that the display might provide him with rundown-times, afterburner times, etc. which are required for his "yellow sheet". Even temperature information during start-up could have been retained and presented at this time. When told that the System would record this information for retrieval by GSE, the subject responded that, "pilots would probably end up doing it anyway".

The secure engines display was adequate in most respects. The simulated sequence was overly simplified, but subjects found the concept of providing checklist information highly advantageous. Throttle commands for taxiing were superfluous.

7.2.14 Miscellaneous Comments

The effective operation of an interactive System such as analyzed in this simulation is dependent not only upon the operator's ability to retrieve information and respond to its requirements, but also on his perception of the operator's role within the loop.

A rationale for the System is based on displaying to the pilot only that information which is necessary to the timely fulfillment of his task.

Subjects were asked about this at the completion of the mission. The intent was to determine (1) whether they agreed that the System did in fact do this, (2) whether they had established any preconceived attitudes toward such a philosophy, and (3) how they envisioned the pilot's reaction to such a role.

Subjects were found to be very open-minded in their critique of the System. There was an obvious tendency to relate back to "their own" aircraft and, as such, their attitudes toward the operation of that aircraft were of interest.

Subjects agreed that "all" information is displayed in "their" aircraft but that the pilot only selects and monitors that information which is important to him at the time. This selection process is accomplished (1) by turning off or on, dim or bright, etc. certain equipment in the cockpit, or (2) by eye scanning only those displays which are relevant.

In effect, subjects acknowledged that pilots only look at what they <u>think</u> they need. Each was somewhat reluctant, however, to let an electronics system do this "thinking" for them. They believed the the System would eventually be appreciated by pilots; and were, perhaps, more impressed with the potentials of the System than with the capabilities which were demonstrated.

All subjects agreed that the displays they witnessed did, for the most part, present only the information required to perform their tasks. They stated that throttle commands were somewhat excessive and redundant; and that compared to real-world operations, the checklists were inadequate.

The consensus among subjects was that if they could be convinced of adequate engine diagnostics, system reliability, and competent sensing and processing of variables, the display philosophy would be acceptable.

7.2.15 Control Functions

This study did not propose to analyze control functions. Nevertheless, a few incidents did occur which are noteworthy and which suggest changes to control or display design for future studies.

Several subjects commented on the location of the engine display compared to the engine controls. They stated that most current aircraft have engine instruments on the left and questioned why this display was on the right side.

Subjects apparently had little trouble finding the controls on the "center panel" and "right hand control console". It was noted on one occasion that a subject depressed ENG 1 AIRSTART instead of ENG 1 START.

Also during the Engines 1 and 2 Start through Takeoff Sequence, there was a tendency on the part of all subjects to manually select ENG 2 START even though the System had automatically performed the operation. It was suggested by them that the selection should be manual.

One subject had difficulty finding the Range Cruise Plot actuator. He apparently did not recognize the legend "RC PLOT." One subject became confused between the ENG 1 AIRSTART mode actuator and the Engine 1 Airstart switch. Some better means should be employed to distinguish between the two.

All subjects agreed that the simulation of controls was good. Controls were well illuminated, provided adequate tactile feedback, and contributed significantly to a high degree of fidelity.

7.3 Comparison of Concept and Display with Current Aircraft Systems

Throughout the flight simulation, subjects were repeatedly asked for their opinions on the way this information was displayed compared to the way it is presented in (their) aircraft.

Subjects almost always responded with two answers. One answer pertained to a comparison between "their" aircraft and the new System concept. The other response pertained strictly to the indicators in "their" cockpit compared to what they saw in the simulator.

A review of Tables C-2 and 3 shows that although some of the IEIS displays may not be an improvement over current aircraft, subjects believed that the potential exists for making them superior.

TABLE C-2 SUBJECT APPRAISAL OF THE CONCEPT COMPARED TO CURRENT AIRCRAFT (MEDIAN RESPONSE)

Sequence	"The concept is ....."
Engine 1 Start - Malfunction	SUPERIOR
Engine 1 & 2 Start through Takeoff	SUPERIOR
Fuel Climb	FAR SUPERIOR
Range Cruise Plot	SUPERIOR
Range Cruise Data	SUPERIOR
Air to Ground/Air to Air Attack	SOMEWHAT SUPERIOR
Malfunction - Delayed Response	SUPERIOR

TABLE C-3 SUBJECT APPRAISAL OF THE DISPLAY COMPARED TO CURRENT AIRCRAFT (MEDIAN RESPONSE)

Sequence	The simulation display was......"
Engine 1 Start - Malfunction	SUPERIOR
Engine 1 & 2 Start through Takeoff	SUPERIOR
Fuel Climb	ABOUT THE SAME
Range Cruise Plot	ABOUT THE SAME
Range Cruise Data	ABOUT THE SAME
Air to Ground/Air to Air Attack	SOMEWHAT SUPERIOR
Malfunction - Delayed Response	ABOUT THE SAME

Subject preferences were obtained for many segments throughout the overall mission. To be meaningful, these responses are related to particular displays. Fuel Climb and both Range Cruise Displays were too static to be much of an improvement over the pilot's present indicators. The Air Attack Display was considered "somewhat superior" because armament information was listed in "plain" English. Thrust and RPM Displays were both designated "superior" to current aircraft instruments. The Engine Malfunction Displays, other than the False Start Display were not so favorably accepted. Subjects were obviously disturbed over the loss of thrust information on the "good" engine.

7.4 Thrust Display Format Comparison (Part IV)

Of primary interest to this study was the introduction and subjective evaluation of two new formats for the Thrust Display. The Thrust Display which was essentially the normal cruise display for the System was modified in various ways to hopefully make it more readable, understandable, and easier to distinguish from the RPM Display. Altogether three identical sequences were developed for a simultaneous presentation of the thrust formats.

The Vertical Scale Format (VSF) was the basic display used throughout the flight mission. All scale numbers were presented and actual thrust values were indicated digitally above the scale (Figures C-26 and C-27).

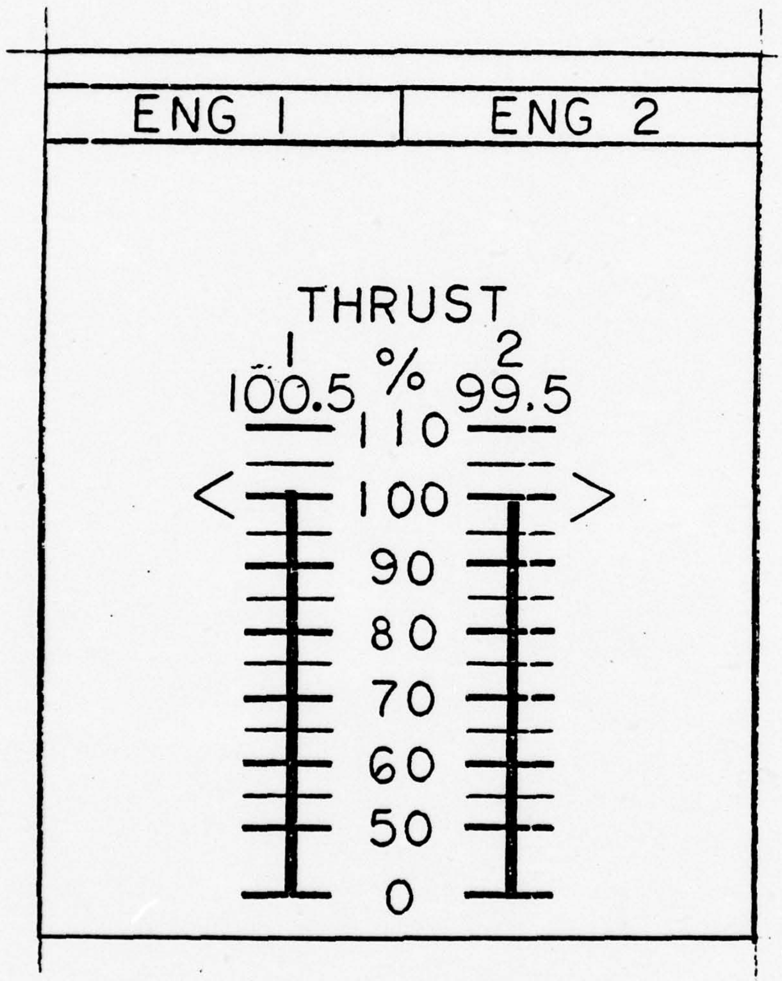


FIGURE C-26 VSF THRUST DISPLAY (THROTTLES 1 AND 2 AT 100%)

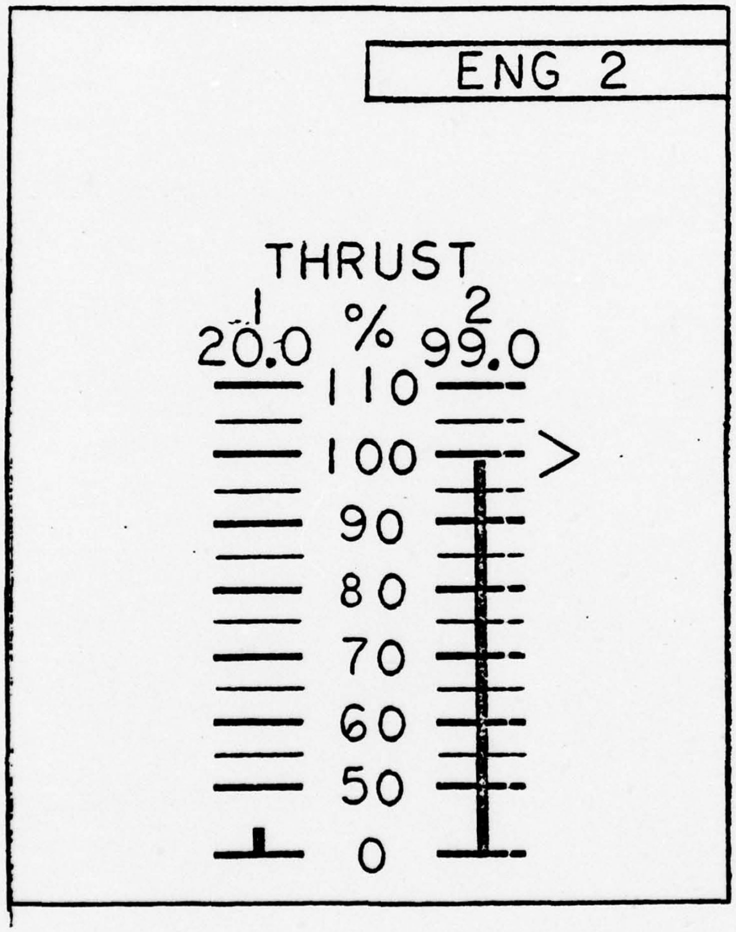


FIGURE C-27 VSF THRUST DISPLAY (THROTTLE 1 AT 18%)

The Modified Vertical Scale Format (MVSF) was similar to the VSF except for abbreviated scale numbers and the location of the actual thrust values to the right and left sides of the scale (Figures C-28 and C-29). These readouts followed the tape up and down the scale as the values changed.

The Triangle Format (TF) was entirely different in appearance and operation than either of the other two. Its intent was to provide an easily understood highly visible indication of the relationship between actual and commanded thrust. The format appeared as one complete triangle when commanded thrust had been achieved; as a segmented triangle when the thrust was outside commanded tolerance (Figures C-30 and C-31). Following the simulated mission the thrust formats were demonstrated two at a time. Subjects were asked to take the appropriate actions required by each display. While still viewing them, subjects were asked to point out which formats best answered the questions of Table C-4.

The purpose of these questions was to elicit subject responses to operational aspects of the Thrust Display. All of the answers required judgement and opinion on the part of the subjects, and as such should be used more as a measure of pilot acceptance than of the effectiveness of the display.

The comparisons were conducted twice. Once using only colored slides and the second time using monochrome slides. The intent was to see what effect the absence of color coding would have on the usefulness of each format.

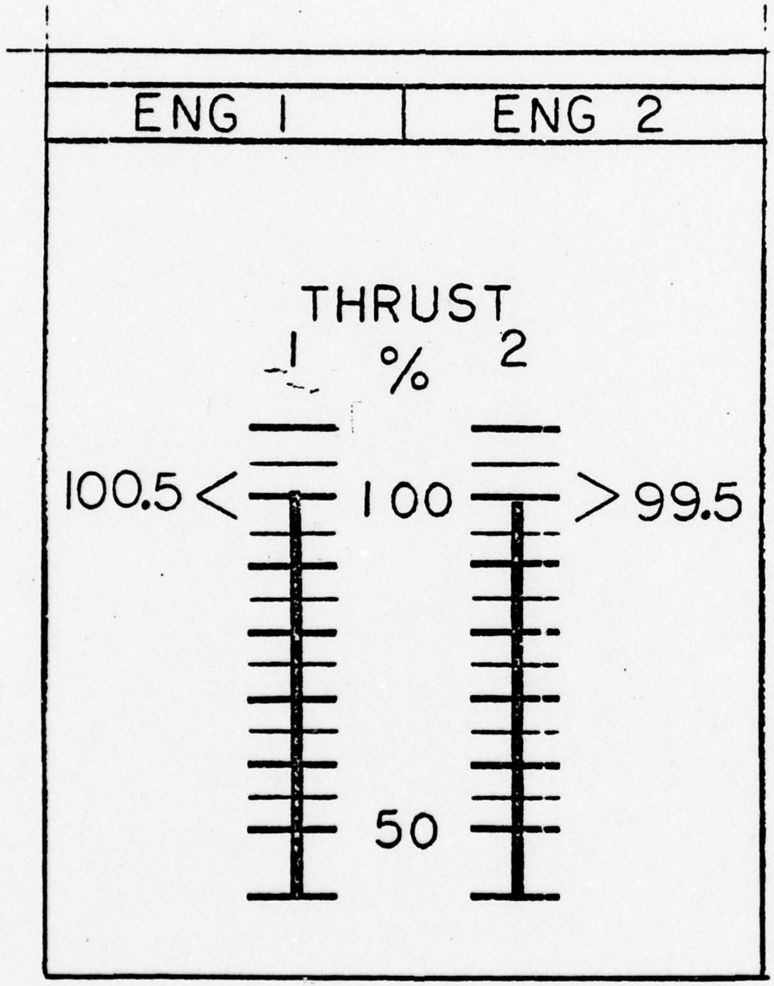


FIGURE C-28 MVSF THRUST DISPLAY (THROTTLES 1 AND 2 AT 100%)

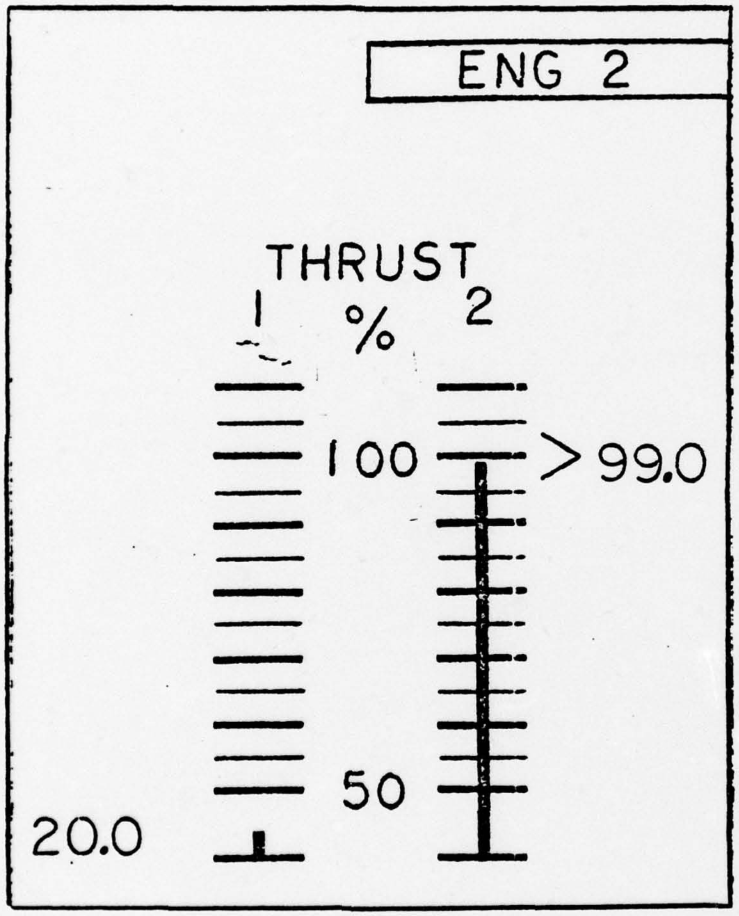


FIGURE C-29 MVSF THRUST DISPLAY (THROTTLE 1 AT 18%)

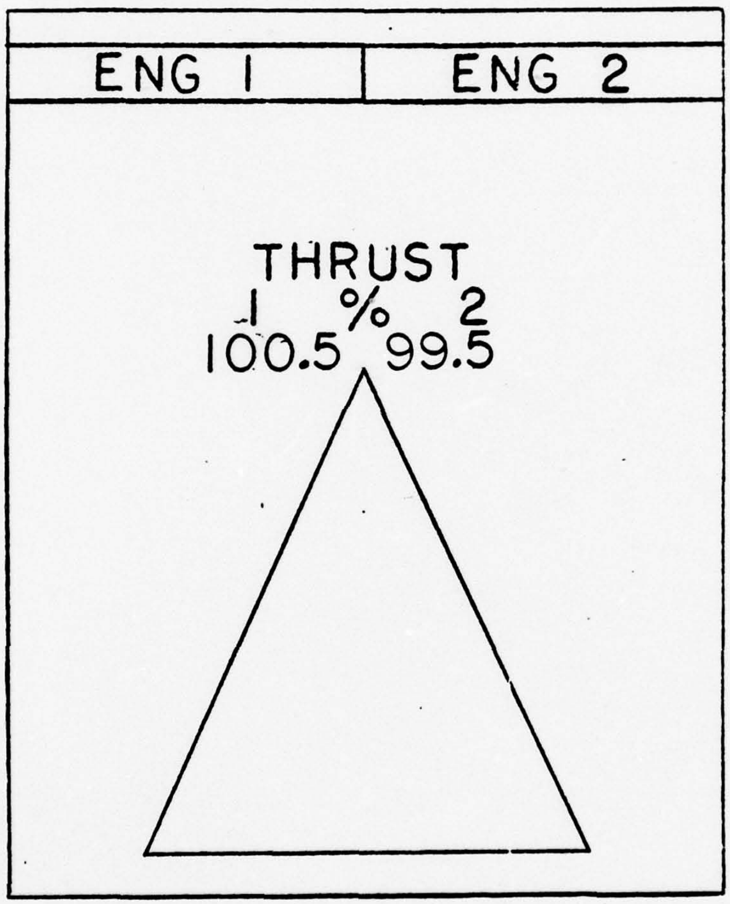


FIGURE C-30 TF THRUST DISPLAY (THROTTLES 1 AND 2 AT 100%)

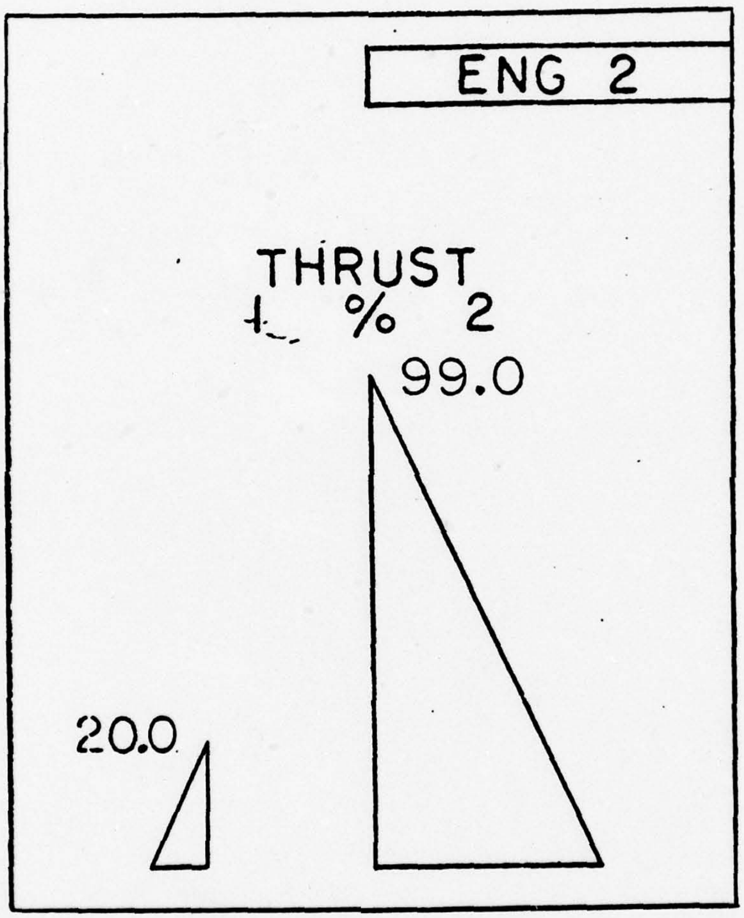


FIGURE C-31 TF THRUST DISPLAY (THROTTLE 1 AT 18%)

TABLE C-4 PART IV QUESTIONS AND PILOT FORMAT PREFERENCE

Question	FORMAT PREFERENCE VSF	MVSF	TF
1. In which of these formats is it easier to-			
a. determine what thrust is commanded?	2	+1	3
b. determine whether the thrust is within acceptable limits?	2	1	3
c. determine the exact percentage of thrust?	-3	1	2
d. monitor the thrust while you are changing it?	2	1	-3
e. determine the exact difference between the thrust of Engine 1 and the thrust of Engine 2?	3	+1	2
f. tell which engine you are controlling?	-3	2	1
g. detect any change in thrust while monitoring a HUD?	-3	2	1
2. Which format best represents your impression of "thrust?"	2	1	3
3. Which format-			
a. is easiest for <u>you</u> to understand?	2	1	-3
b. would be easiest for a student pilot to learn?	2	1	3
4. Which format suggests to you the greatest-			
a. accuracy?	1	2	-3
b. simplicity in appearance?	-3	2	+1
5. In general, which color format do you prefer to the thrust display?	2	1	3
6. In general, which monochrome format do you prefer for the thrust display?	-3	1	2

1 - Most Preferred
2 - Second Most Preferred
3 - Least Preferred
+ - Significantly Greater Preference
- - Significantly Lesser Preference

7.4.1 Color Format Comparison

Because of the small sample size used in this study, the usual statistical analyses were waived for a simple conversion of subject responses to percentage. This measure, although not powerful, provides a good relative indication of which formats appealed mostly to the subjects and identifies the degree of each format's strengths and weaknesses. In general, the measure helps to shed some light on the relative importance in differences between the three formats. These percentages are shown in Table C-4.

One of the most significant and obvious differences between formats was their "simplicity in appearance." Subjects rated the TF as most simple in appearance, the MVSF next, and the VSF as not simple. Several subjects stated that "simplicity in appearance" was not necessarily a relevant feature in display design. It is ,however, very desirable if all factors involving information content and operation are equal.

Another impressive finding was the subjects' perception of which format "suggested the greatest accuracy". Ratings between the VSF and MVSF were similar. The TF, however, was perceived as much less accurate than either. If, as discussed previously, trends, speeds, and relative differences are more important than absolute values for thrust; then perhaps high absolute accuracy is not a Thrust Display requirement. It was probably the presence of scales which was responsible for the higher "accuracy" rating of the VSF and MVSF.

When asked from which format it was easiest to determine the difference between Engine 1 and Engine 2, a very significant number of responses favored the MVSF. The TF and VSF were rated about average.

Further analysis revealed a consensus in favor of the MVSF for almost all questions relating to a quick and accurate determination of thrust. As shown in Table 2, the MVSF was chosen as an easy display to (1) determine what thrust was commanded, (2) monitor the thrust while it was being changed, (3) determine when the thrust had reached and maintained acceptable limits, and (4) determine the exact percentage of thrust. The TF faired least well on three of these.

When it came to telling which engine was being controlled, or detecting a change in thrust while monitoring the HUD; both the TF and MVSF were favored. Subjects were quick to add, however, that pilots would not expect to get this information <u>initially</u> from the engine display.

In response to the question, "Which format is easiest for you to understand," subjects favored the MVSF. The TF apparently was not well understood or at least they did not think they understood it. Ironically, when asked which format would be easiest for a student pilot to learn, no one format was singled out.

Finally, subjects were asked to select an <u>overall</u> preferred format for the Thrust Display. Again no single format stood out above the others.

It can be concluded from the above discussion that none of the formats presented were overwhelmingly favored in all aspects of display design. None, on the other hand, were totally rejected. The finding is consistent with conclusions presented elsewhere in this report. It demonstrates the need for further identification of pilot requirements and a refinement of displayed information.

7.4.2 Monochrome Format Comparison

The same procedure used in evaluating the color formats was used for the monochrome comparison. All slides were green. Subjects observed and responded to all the same sequences. They were, however, asked only one question; "In general, which monochrome format do you prefer for this application?"

The total absence of primary cues was the chief complaint of subjects when they first viewed the monochrome formats. According to one subject, contrast between orange and green on the colored formats made the tape and caret most discernible of all the display elements. This was why they and not the digital readouts were used continuously as indicators of engine performance. It is not surprising, therefore, that the monochrome VSF was considered significantly poorer than the other formats. The MVSF and TF utilized coding other than the tape and caret to indicate actual engine thrust. It must have been quite obvious even in green.

This study concludes that the upper portion of the VSF appears unnecessarily cluttered. Both the engine numbers and percentage symbol may be eliminated. If unique formats are adopted for RPM and thrust, and the indicated parameter is extremely evident, the labels "RPM" and "THRUST" may be eliminated.

Engine status bars are well located. The concept of continuously displaying these positive indications was appreciated. Their silhouette, however, contributed significantly to cluttering the format.

To solve this problem and to augment detection and interpretation, it is recommended that the bars be solid color with black characters on the green background. It is not known whether the two bars should be joined or separated.

An investigation should be undertaken into the possibility of changing the moving tape indicator to a movable pointer. This recommendation is based on the fact that subjects received their information cues not from tape length, but from the relative location of the top of the tape and scale indices or carets.

Another way of making the parameter value more obvious on the scale might be to make that particular graticule which represents the value change color.

Caret shape and orientation must be improved. Its design is a function of System commands and tolerances, and as such can be specified only after its real purpose and requirements are defined. A significantly more meaningful indication would be created if caret mechanization and intent were revealed in its design.

The analysis and comparison of monochrome formats was intentionally de-emphasized. Experimenters acknowledged that if the color capability did not exist initially, the display format and operation would probably have been designed very differently.

8.0 Conclusions and Recommendations

The following conclusions and recommendations are based on the findings of Section 7.0. Information display, dynamics and arrangement changes to the formats, as well as areas requiring additional investigation, are presented.

8.1 Self Test Format

The self test format is adequate. Its usefulness could be significantly enhanced through the addition of a "self test in progress" indication. Diagnostics or "pilot instructions" should be displayed in the event of a failed test. The failed test indication must be made obvious. The "test passed" format might incorporate a test pattern or "flooded screen" to demonstrate proper display operation.

The self test feature must be mechanized to permit its activation at any time for a "display test" with minimal loss of engine or supplemental information. Color coding was appropriate.

8.2 Fuel Climb Format

The fuel climb format, as shown, is a mundane utilization of an otherwise invaluable display. Its static nature and lack of flexibility made it little more than a duplication of the pilot's original take-off and climb-out plan.

The display should be mechanized to show re-computed curves and their consequences from both present aircraft position and projected positions. The display should also permit pilot interaction for inputting hypothetical situations and conducting fuel vs. performance tradeoffs.

An investigation should be conducted into the presentation of additional parameters. Thrust and/or RPM values may be required as well as consumable information since this is a "fuel critical" display. Both real time and optimal information should be presented.

The graphic format was easily understood and should be retained. Color coding likewise is functionally consistent.

If deviation from track tolerances are desired, "bug" size could be varied to indicate the tolerance. When the "bug" is "on track" it and/or the track could change color. Variations in coding and format should be explored for all the contingencies inherent in an optimized fuel climb.

The possibility of adopting this display for other optimizations such as minimum time climb should also be studied and tested.

8.3 Range Cruise Plot Format

The range cruise plot format would be used only when the aircraft is under control by data link or a programmed flight profile.

As a result of this study, effectiveness of the "plot" format is questionable. The display, in all probability, would be used infrequently and then only to obtain low priority flight profile information.

The format, if it is retained, should contain both real time and optimal information. There should be provisions for the continuous display of at least one engine parameter. Where evolutions are indicated in the profile, the format should provide detailed information on how they are to be accomplished (eg. reduce power, dive, etc.).

If this display were tied in with fuel or time optimization criteria, it would be helpful to the pilot. Similar to the Fuel Climb Display, it should be mechanized to accept pilot inputs and in turn present profile options for various hypothetical problems. The display might be particularly useful in "fuel critical" situations.

Graticules on both scales should be re-designed to increase reading accuracy. As in the fuel climb format, "bug" size could be made to vary according to tolerance and both track and "bug" colors could be mechanized to change.

In general, the lack of effectiveness of this format and its anticipated low utilization by the pilot suggests that range cruise information could be better utilized in a predictor display than in a past or current situation indicator.

A definite need is established to look into the possibility of combining the information of the Range Cruise Plot and Range Cruise Data Displays into one format.

8.4 Range Cruise Data Format

The single foremost advantage which secured a greater acceptance for the range cruise data format was the retention of engine information. As in the "plot" format, considerable real time and optimal information as well as how to accomplish each evolution should be presented. Pilots may also require a continuous display of fuel flow.

If the addition of all this information to the basic Thrust Display appears crowded, then the adoption of an abbreviated thrust indicator may be warranted.

The possibility of re-formatting all range cruise information into a composite display is again emphasized.

8.5 Vertical Scale Format (VSF)

The basic vertical scale format was accepted as a viable indicator of both engine RPM and thrust. There was not enough difference between the two displays however, to avoid confusion. It is suggested that if the vertical scale format is used as an indicator for one of the engine parameters, a totally different format should be chosen for the other.

System mode could be better indicated on the mode selection actuator than at the top of the screen. If display information is both timely and sufficient for the particular evolution, then there should be no need to display System mode on the screen.

The general arrangement of components on the VSF was satisfactory. Written material, however, was overly crowded both within and between words. Character size may have been excessive. Better coding surely could have been accomplished by a variation in character size. Line widths were adequate. The moving tape should be at least 50% wider.

Future simulation should be designed to exactly replicate the display characteristics of proposed hardware. Character fonts, spacing, lines, color and brightness should be considered an integral part of the next display evaluation.

Digital readouts were of use to the pilots only after pilots had achieved the power setting they desired. Changing numbers gave them an indication of fine control where tape position aided coarse control. Actual percentage should be written to the nearest units. Digit blanking and stability must be examined in order to assure a readable indication.

The use of variable <u>length</u> graticules on the RPM scale was far superior to the variable <u>width</u> graticules of the thrust display. Both the minor indices and full compliment of scale numbers should be retained. The condensed 0-50% portion of the 0-110% scale also proved to be effective.

This study suggests that a one-to-one relationship between indicator movement and throttle change may be a very desirable feature. The advantages should be explored for both RPM and Thrust Displays. It could conceivably be accomplished by compensating throttle movement or displaying a non-linear scale.

8.5.1 <u>RPM Format</u>

The VSF was employed quite effectively to display both 0-50% and 0-110% engine RPM. Scale changes could have been better identified although this was not recognized as a problem during the simulation.

Presentation of checklist information was appropriate although artificially brief. The moment of engine "light-off" is important and should somehow be indicated. Written throttle commands except for checklist position should be avoided. If written RPM commands are required they should be labeled "RPM" not "THROTTLE", otherwise symbolic commands (ie. carets) are adequate. The carets should return to zero once a pilot is committed to shutting down the engine.

It is recommended that an extensive start sequence, one more representative of a particular engine type, be developed and tested using this format. Several questions remain unanswered. What other engine parameters must be displayed? Should "IDLE", "INTERMEDIATE", and "MIL" (i.e. throttle settings) be indicated on the RPM scale?

Once the engine has reached idle, RPM commands should be extinguished. If an engine "check out" procedure is initiated and specific throttle settings are dictated, then commands may be displayed. Again, during engine run-up or a "check out" phase, the display of additional parameters may be desirable.

In landing, the Thrust Display should be maintained, at least, until touch down. More study must be made of this proposal however. If a "touch and go" is initiated, the System might be "caught" in an RPM - taxi mode when, in fact, a thrust-take off mode is required.

There should be no written thrust or RPM commands during landing. If the aircraft is on a data link, ACL, fuel or time descent; symbolic commands are adequate.

The RPM Display was well suited for securing engines. Again the check-list was extremely oversimplified but effective. Throttle commands, written or symbolic, should not be displayed for taxiing or shut-down. Following shut-down, "yellow sheet" information could be provided to the pilot. Whether this will be a requirement in future aircraft is not known.

.8.5.2 Thrust Format

Thrust VSF would have been more easily accepted by the subjects if they had been acquainted with the measurement and meaning of thrust. This lack of understanding caused considerable apprehension about being able to monitor only the one parameter. It is recommended that all future studies include a training or orientation period to thoroughly acquaint subjects with the tested parameters and display characteristics.

It is concluded that thrust is a viable parameter to display during flight, but that the real need to include other parameters with it should be investigated. Both fuel flow and engine temperatures may logically be included on the format. The requirement to monitor consumables is a function of aircraft type and mission, and may most appropriately be presented only during certain operations.

Afterburner position is not indicated on the display, but probably should be.

The proper time to present thrust is during take-off and normal flight. Thrust should also be presented in the supplemental flight display and the engine malfunction display if it is adopted as the primary flight parameter.

Written throttle commands should be eliminated entirely. When thrust commands are relevant to the operation of the aircraft, symbology (i.e. carets) is adequate.

In general, the thrust VSF was the least acceptable format of the thrust display. Based on the findings illustrated in Table C-4, this format is not recommended for further development in the System. Also, this format should not be displayed monochromatically.

8.6 Modified Vertical Scale Format (MVSF)

Among the three thrust formats, the MVSF was the most accepted. MVSF popularity was attributed to its similarity with the kind of indicator pilots use "today" and the "easy to see and interpret" digital readouts.

This technique, in fact, was so satisfactory that it made the tape indication almost a redundancy. It is conceivable that a pointer could be attached to the digital readouts and the tape eliminated. Further, the digital readouts could be coded so as to display different parameters to the pilot all on the same format skeleton.

One such proposal is illustrated in Figure C-32. Obviously this is a "rough sketch" compared to the kind of format which will satisfy all requirements. Nevertheless it is an example of the trend to which the results of this study point.

The abbreviated scale numbering system used on the MVSF is not recommended. Also, variable length rather than width graticules should be used.

In general, this was an easily understood, readable, and attractive format. Its arrangement makes it suitable but not recommended as a monochrome display. Based on the findings of Table C-4, it is concluded that this format's capability could be optimized with minimum effort. The MVSF is recommended for further development.

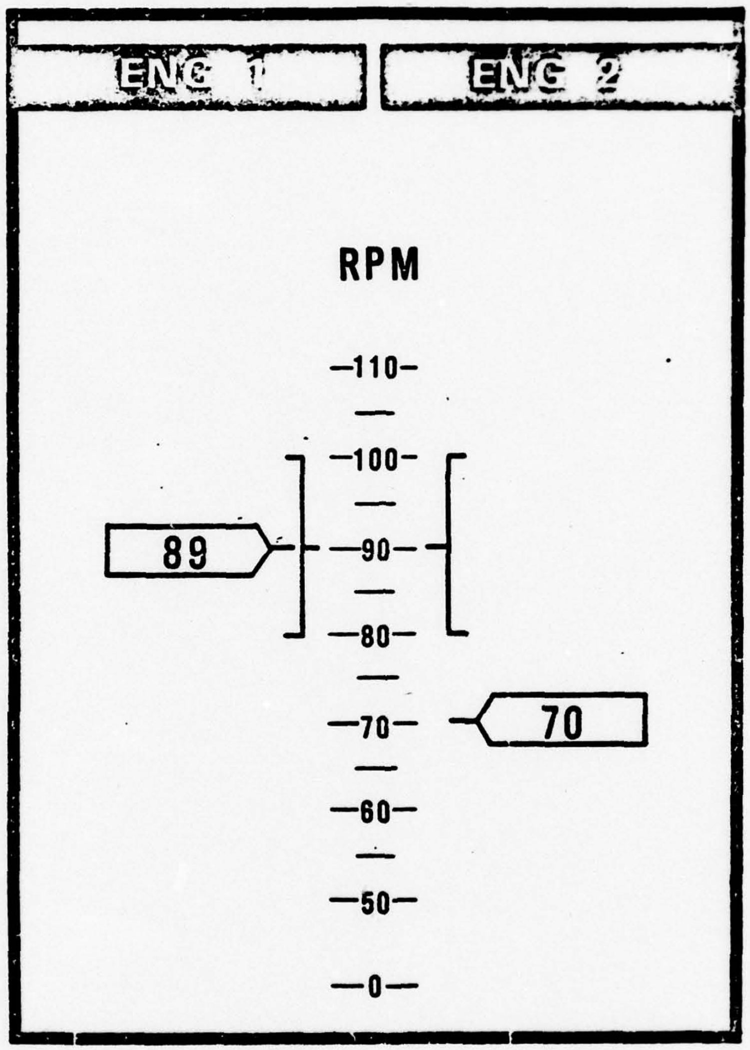


FIGURE C-32 SUGGESTED MODIFIED VERTICAL SCALE FORMAT

8.7 Triangle Format (TF)

The major disadvantage experienced in the evaluation of the TF was a general lack of in-depth understanding by the subjects. This was evidenced by the nature of the questions subjects asked and an observation of their actions.

The study was not biased by this problem, but it is felt that subjects were insufficiently exposed to the TF to fully appreciate its capabilities. For this reason, it is recommended that a detailed scenario of the TF should be developed and evaluated. One which demonstrates its capacity through all contingencies of engine operation and flight.

The greatest problem which subjects had in using the TF was their inability to tell what the completed triangle should look like. They questioned how the format would appear during afterburner. They also wanted some indication of the tolerance values. Subjects suggested that scales or "bench marks" be incorporated with the triangle. There are, however, no substantiated reasons to recommend this and further study is recommended before any decision can be made.

Deviation from tolerance changes were, of course, easiest to detect on the TF. The format was most simplistic in appearance but did not connote accuracy. In general, subjects felt more compelled to read the digital readouts since they were unable to obtain minor trend information from the large triangle. The location of these readouts along the sides of the triangle was perhaps less helpful than anticipated.

The TF was highly visible in the subject's periphery. Its use in a monochrome display is possible, but not recommended.

In general, this type of format exhibits an enormous potential for good thrust indication. Pictorial displays have proven effective when properly designed. Only a complete "work-up" of all operational aspects of the thrust display can reveal the true utility of the triangle or other pictorial presentation.

8.8 Engine Malfunction Format

The engine malfunction format is undoubtedly the most dynamic of all data presentations. To be effective, it must present the pilot with diagnostic and procedural information in an arrangement easily discernible during high stress periods.

The format was evaluated through two sample engine malfunctions, false start and engine lub loss. The malfunctions demonstrated well the tremendous usefulness of the format to inform the pilot of his problem and provide a checklist of required actions.

The most striking characteristic of the format was the ease with which it was detected and understood. The engine malfunction format must remain signficantly different in appearance than the normal flight formats. It is recommended that the primary engine parameters (ie. thrust, RPM, etc.) be included in the malfunction format, particularly for operation of the remaining engine.

A description of the malfunction, its consequences and options should also be presented instead of the words "secure engine".

Color coding and dynamics of the horizontal scales were very effective. The color of written information on the screen should reflect the criticality of that information, but did not. As an example, for a marginal situation, the engine designation and fault diagnosis (ENG 1 lube loss) should be yellow. For a critical situation, they would be red.

Spacing, separation between elements, and character size must be improved. Tic mark vectors may be omitted.

Based on the overhwelming desire for continuous trend information, but the insistence by many subjects that absolute measurements are of value; it is recommended that the present method of presenting marginal and critical information be retained.

This report further recommends the development and evaluation of additional engine malfunctions using this format. The purpose would be (1) to ascertain if all engine malfunctions can be presented this way, (2) how the format would react to all variations of control and operation, and (3) how compound malfunctions and multiple-engine failures would appear. It should be possible to develop a format which will provide the required information of all malfunction contingencies on a "bad" engine while continuing to display the normal operating parameters of the "good" one.

8.9 Air-to-Ground/Air-to-Air Attack Format

The findings of this study relative to the effectiveness of the attack format are inconclusive. Based on the conflicting evidence of what engine information is required during attack, the whole idea of presenting weaponry information on the IEIS display may be inappropriate. Only through further investigation into the information requirements of an air attack, can this dilemma be resolved.

If the display of weaponry information at this location is deemed appropriate and useful, the format would require significant modification.

Some provision should be made for continuous indication of primary engine parameters. The format should also present only that armament relevant to the selected mode (ie. air-to-ground or air-to-air). Information about the armament station, missile selection and control, and missile status must be much more comprehensive. Symbology and missile designations may be used. A pictorial format with weaponry arranged similar to its physical location on the aircraft would be desirable. This approach should be investigated.

Color coding, abbreviations, and operating sequences should be reviewed to more authentically replicate actual weaponry systems. In general, appearance of the format could be greatly simplified.

It is recommended that the Air-to-Ground and Air-to-Air Attack Sequences be re-defined and that a scenario depicting all possible contingencies during the attack be developed. Variations of the existing formats as well as proposed new formats could then be tested to see how effectively they convey the required information.

8.10 System Controls

All controls were adequate for the degree of fidelity required in the simulation. They were well illuminated.
Control operability was not evaluated.

For future simulation is is recommended either that controls be installed in a location similar to the pilot's "own" aircraft, or that he be more extensively briefed on where to find them and what they do.

A rationale for which modes are "aircraft" oriented and which are "System" oriented must be established and so indicated.

Engine airstart switches should be protected or made more distinctive.

8.11 Cockpit Integration and Compatibility

The simulated VSD, HSD and LHSD (see Section 6.0) contributed only cursory information to the study. Although the displays provided subjects with a sample of the kind of information and format which would be presented elsewhere in the cockpit, few subjects took the time to extract much information from them.

From a purely "appearance" standpoint, all displays were relatively compatible. Color quality and character size/style could have been better coordinated.

It is recommended that future studies make greater use of all cockpit indicators. This would be possible through more extensive scenario development and the sequencing of all cockpit indicator slides on a one-for-one basis.

Only then can the effectiveness of total cockpit information and integration of dynamics be realized.

8.12 The Study

The entire study, as evidenced by the overabundant wealth of information reported, must be termed a great success. The primary shortcoming was its brevity and the inability to evaluate the many possible contingencies of each event.

Participation of the subjects and cooperation of the facility personnel were exemplary.

The 35 mm slide technique is recommended as an inexpensive, extremely versitile and flexible mechanism for administering future simulations of this nature.

It is further acknowledged that the random access capability would be well suited to sequences where the pilot could exercise various options, and observe their outcome.

It is concluded that the method of scenario development, subject selection and simulator design was most appropriate to the study. With minor changes, the same procedure and facility is recommended for succeeding studies.

9.0 Future Activities

The Phase V Evaluation was the first exposure of the IEIS formats, in the reduced display size, to pilot critique. As was discussed in the previous sections there were many format and data recommendations that were identified for incorporation into these formats. The IEIS Program has been an iterative process from its inception through to the present and as such it is recommended that these format modifications be investigated in the next Program Phase. To accomplish these format iterations and to continue development of the IEIS Display the following activities are recommended for the next program phase.

9.1 Display Information Options

There are many ways for presenting or formatting the same data for display to the pilot. Three presentation options for displaying "THRUST" were given a limited investigation by the Phase V Evaluation. An expansion of this effort is recommended to better identify the "optimum" means presenting specific pieces of data and the feasibility of providing a functional display of engine status.

While the pictorial presentation did not receive a favorable reaction from the Phase V Evaluation, it is felt this is a viable display technique and should be given a more thorough evaluation.

It is recommended, as a minimum, that the following category of display options be investigated:

Additional Geometric Symbology

Pictorial Presentations

Color

Use of Coding Techniques

Functional Displays

This investigation should establish a set of recommended display techniques for presenting specific types of information to the pilot.

This display information option investigation would encompass three basic tasks, they are:

- Identification of Display Options
- Evaluation of these Options to Select the "Best" for IEIS Usage
- Functional Display Definition

9.2 VSTOL Considerations

The IEIS effort to date has not addressed the engine display requirements posed by VSTOL operation. The present display concept for presenting normal status and malfunctions should suffice for the VSTOL case, however, there are additional areas where investigation is warranted.

One area where the IEIS display could be utilized is in the area of thrust vectoring for all flight phases of vertical, horizontal and transitioning. This task would encompass an information analysis effort to determine what the pilots information needs are for these flight phases. Having determined the information needs, formats would be established for displaying this information to the pilot in the most useful form.

In addition to this IEIS VSTOL display, effort should be directed toward determining what minimal engine status information needs to be displayed on the HUD during landing. Because of the difficulty of the task, the VSTOL aircraft will probably be HUD landed. It will be necessary to present certain engine status information and probably thrust vectoring information on the HUD.

Again how much of this information is needed will have to be determined and then properly formatted for HUD presentation.

This information analysis and formatting would benefit greatly from the previously addressed effort and would be a natural follow on to it. The basic tasks for this effort will be the following:

- Integration of Engine Parameters into Functional Displays
- Determination of Best Method of Displaying these Functions

9.3 Display Formats

During the course of the Phase V Evaluation there were comments and questions regarding "other" display formats that were not shown. These included a Time Climb Profile, a multiple fault situation, and a landing checklist display and there are undoubtedly many others.

As new and revised formats are generated a concerted effort should also be undertaken to "complete" the IEIS display library. This effort should attempt to identify and generate all the display formats that are displayable on the IEIS display in its role as an engine monitoring display. This activity would greatly enhance future evaluations, as there would be no "holes" and the total display capability could be demonstrated.

9.4 Evaluation

It is recommended that the evaluation effort of the IEIS concept and formats be continued. The three previous discussions recommend development of new or revised formats as does the results of the Phase V Evaluation. These iterated formats will require evaluation to determine if they do respond to pilot preference and needs.

Initially a "Static" evaluation along the lines of the Phase V effort is recommended. This is a cost effective means for evaluating many display options and for obtaining pilot preference.

However, when a set of baseline formats have been established through static evaluation, a dynamic evaluation should be conducted. This evaluation should have dynamic display presentations with active pilot interaction with the displays. This would provide not only an indication of pilot preference but would also provide the opportunity to quantitatively measure reaction times and errors made in reading the displays.

APPENDIX D

IEIS SENSOR SURVEY

IEIS SENSOR SURVEY

LIST OF FIGURES

1.0 INTRODUCTION

An important part of IEIS Phase V was an investigation of sensor technology which identified current "standard" sensor performance characteristics. Where current sensor technology was found inadequate for IEIS input parameters, technological trend projections and expected functional characteristics were identified. The objective of this effort is to ensure that IEIS requirements and future sensor capabilities are synchronized for the 1980-85 time frame.

Any attempt at projecting technological trends must include consideration of the various forcing functions involved. For the IEIS engine concept in the 1980-85 time period, these forcing functions and their effect are summarized as follows:

1. Application of microcomputers in engine controls and flight condition monitoring will result in a family of sensors having outputs which should be digital in nature.

2. Higher performance engines will result in more demanding operating ambients.

3. Compact, non-immersion probes for control and performance monitoring will be developed to replace the currently used immersion types.

4. Transient engine condition monitoring will require sensors with improved response times.

5. Generally opposing forces of careful cost control on the one hand versus higher reliability via more engine sensors and performance monitoring on the other will hinder rapid engine instrumentation developments.

The ideal sensor for IEIS must output a serial digital word to a data bus when addressed from the same bus while still meeting all of the reliability, cost and performance constraints. An assessment of current technology and the divergent forces identified, indicates that the "ideal" sensor will not be available in the 1980-85 time frame. However, sensors having outputs which are easier to handle by digital techniques will be available. The sensor matrix provides an assessment of what progress can be realistically expected.

2.0 MATRIX TERMS AND DEFINITIONS

The IEIS sensor matrix provides identification of key functional and performance data for both the aircraft industry accepted "current standard" and the future devices which will satisfy the IEIS "projected need" in the 1980 to 1985 time period. Only parameters measured "on engine" are included in the matrix. These are identified by accepted terminology and are generally grouped by the type of measurement involved, such as pressure, temperature, position, etc. Other IEIS inputs such as air data are realistically assumed to be obtained over a digital data bus in accordance with the required accuracy and response time constraints, using currently available technology and are therefore not included.

The IEIS sensor matrix headings and subheadings were selected to provide a view of all pertinent sensor information. The following paragraphs contain an explanation of the matrix format.

Parameter

Under this heading are listed all IEIS required parameters by accepted name and symbol. Since all parameters are measured by engine mounted sensors, the letter "E" appears under "location". Parameters are grouped in general for pressure, temperature, etc.

Purpose

Sensor outputs serve five distinct purposes under the IEIS concept. An "X" under the following headings shows the function of each parameter:

- "Display" indicates that the parameter is displayed to the pilot on a selected basis.

- "Engine Control" indicates that the parameter is used by the electronic engine control unit.

- "Fault Det./Isol." indicates that the parameter allows detection of an engine malfunction and isolation of the malfunction to a location or component.

- "Record Keeping" indicates that the parameter is used for record keeping. Examples of recorded data are time, date, engine S/N, and aircraft S/N.

- "Health Trending" indicates that the parameter is used for prognostication of engine wear and failure.

Interface

Under this heading are definitions of concept. Electronic signal conditioning and formatting into digital data are accomplished by the engine control unit, the IEIS system, or other aircraft systems.

Current Standard and Projected Need

The current capability and future needs of sensors are shown under the following headings:

- Type: This column identifies the basic sensing technique employed.

- Range: Specific data provided covers the F404 engine operating envelope but should be fairly representative of future variable cycle engines of equivalent size.

- Output Signal: The basic signal format is identified. Unless otherwise specified, the signal can be assumed linear. In most cases, however, some linearity refinements will be required.

- Accuracy: This parameter defines the required long term performance (1 to 2 years) in the service environment.

- Repeatability: Repeatability is defined as the allowable short term variation in readings (within the accuracy requirements) obtained before and after exposure to typical service environments. Among the factors included in short term variation are hysteresis, noise and resolution.

- Frequency Response: The value provided represents the -3DB bandwidth for the sensing system. For pressure parameters, this would include the effects of probes, lines and cavaties.

- Temperature: Expected temperature extremes in the area of the sensing element are identified, based on an assumed sensor location on the engine.
- Vibration: Vibration levels typical of those used for component bench qualification are provided. Normal frequency range would be 20 to 2000 Hz but each engine application may have discrete resonances.

3.0 SENSOR MATRIX

IEIS SENSOR MATRIX

	PARAMETER						PURPOSE			INTERFACE	CURRENT STANDARD								PROJECTED NEED								
NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	COMMENTS
1	Engine Inlet Total Pressure	P1	E		X			X	X			TP Probe Strain Gage X'DCR	1.4 to 40 PSIA	DC 50 MV fs	1% Total Error Band	.2% fs	100	-65 to +250	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-linear	0.5% fs	0.1% fs	1K	-65 To 400	30	Mount Transducers Close to Probe to Reduce Line Effects
2	Core Comp. Inlet Total Pressure	PT25	E		X	X		X	X			↓	1.4 to 50 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
3	Fan Duct Pressure Ratio	PDQS	E		X			X	X			↓	0 to 0.2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
4	Core Comp. Exit Static Pressure	PS3	E			X		X		X		Wall Probe Bourdon Ratio	0 to 400 PSIA	400 Hz Sine 5 to 15V RMS	3% fs	1% fs	10	-65 to 400	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
5	Gross Thrust	FG	E			X		X		X																		See Text
6	Stall Margin	Stall	E			X		X		X		Use PS3 & PDQS Rate	Calculated Parameter - Use Rate of Change of PS3 & PDQS to Determine Impending Stall															Engine Control Response Time Not Good Enough to Recover Based on Stall Input
7	Oil Pressure	PL	E	X		X		X				Bourdon Ratio	0 to 500 PSID	400 Hz Sine 5 to 15V RMS	3% fs	1% fs	10	-65 to 400	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-linear	3% fs	1% fs	1K	-65 to 400	30	Measure Pulsation Level to Determine Health of Pump
8	Oil Filter Delta Pressure	FLDP	E			X		X		X		↓	0 to 20 PSID	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
9	Scavenge Pressure	PLS1 to PLS4	E			X		X		X		↓	0 to 100 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
10	Main Fuel Pump Discharge Pressure	PWFM	E			X		X		X		↓	0 to 1200 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
11	A/B Fuel Manifold Pressure	PWF6	E			X		X		X		↓	0 to 1200 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
12	Fuel Filter Delta Pressure	FFDP	E			X		X		X		↓	0 to 100 PSID	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	

IEIS SENSOR MATRIX

PARAMETER				PURPOSE					INTERFACE			CURRENT STANDARD								PROJECTED NEED								
NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	COMMENTS
1	Engine Inlet Total Pressure	P1	E		X			X	X			TP Probe Strain Gage X'DCR	1.4 to 40 PSIA	DC 50 MV fs	1% Total Error Band	.2% fs	100	-65 to +250	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-linear	0.5% fs	0.1% fs	1K	-65 To 400	30	Mount Transducers Close to Probe to Reduce Line Effects
2	Core Comp. Inlet Total Pressure	PT25	E		X	X		X	X			↓	1.4 to 50 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
3	Fan Duct Pressure Ratio	PDQS	E		X			X	X			↓	0 to 0.2	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
4	Core Comp. Exit Static Pressure	PS3	E			X		X		X		Wall Probe Bourdon Ratio	0 to 400 PSIA	400 Hz Sine 5 to 15V RMS	3% fs	1% fs	10	-65 to 400	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
5	Gross Thrust	FG	E			X		X		X																		See Text
6	Stall Margin	Stall	E			X		X		X		Use PS3 & PDQS Rate	Calculated Parameter - Use Rate of Change of PS3 & PDQS to Determine Impending Stall															Engine Control Response Time Not Good Enough to Recover Based on Stall Input
7	Oil Pressure	PL	E	X		X		X				Bourdon Ratio	0 to 500 PSID	400 Hz Sine 5 to 15V RMS	3% fs	1% fs	10	-65 to 400	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-linear	3% fs	1% fs	1K	-65 to 400	30	Measure Pulsation Level to Determine Health of Pump
8	Oil Filter Delta Pressure	FLDP	E			X		X		X		↓	0 to 20 PSID	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
9	Scavenge Pressure	PLS1 to PLS4	E			X		X		X		↓	0 to 100 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
10	Main Fuel Pump Discharge Pressure	PWFM	E			X		X		X		↓	0 to 1200 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
11	A/B Fuel Manifold Pressure	PWF6	E			X		X		X		↓	0 to 1200 PSIA	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
12	Fuel Filter Delta Pressure	FFDP	E			X		X		X		↓	0 to 100 PSID	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	

IEIS SENSOR MATRIX

	PARAMETER						PURPOSE			INTERFACE	CURRENT STANDARD							PROJECTED NEED								
NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	COMMENTS
13	L.P. Turbine Inlet Total Pressure	P49	E			X		X		X		TP Probe Bourdon Ratio	0 to 100 PSIA	400 Hz Sine 5 to 15 V RMS	3% fs	1% fs	10	-65 to 400	20	Vibrating Quartz Crystal	Same	Variable Freq. at 100K Hz Non-linear	3% fs	1% fs	1K	-65 to 400	30	TP Probe Ahead of LP Turbin is Major Reliability Concer May Want to Include Probes i Leading Edge of Several Stator Vanes.
14	Engine Inlet Total Temp.	T1	E		X	X			X			RTD Probe	-65°F to +400°F	Res. Chg. with Temp. Platnium	1.0°F	0.7°F	0.2	-65 to +400	30	Wall Mounted System	Same	Variable Freq. Sq. Wave	Same	Same	10	Same	Same	See Text
15	Core Compressor Inlet Total Temp.	T25	E			X		X		X		RTD Probe	-65°F to 900°F	↓	↓	0.2°F	0.2	-65 to +900	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
16	Core Compressor Exit Total Temp.	T3	E			X		X		X		T/C Probe	-65°F to 1200°F	50 MV DC Full Scale	5°F	1°F	0.5	-65 to 1200	↓	↓	↓	↓	2°F	0.5°F	↓	↓	↓	↓
17	High Pressure Turbine Blade Temp.	T4B	E	X	X	X		X	X			Optical Pyrometer	1000°F to 2000°F	Non-linear DC 10V FS	+10°F to -20°F	5°F	10K	-65 to 800	↓	Same	400°F to 2000°F	Same	5°F	2°F	10K	-65 to 800°F Fuel Cooled	30	T/C Used to Extend Operatin Temp. Below 1000°F, See Text.
18	L.P. Turbine Inlet Total Temp.	T49	E			X		X		X		T/C Harness	-65°F to 2000°F	80 MV DC Full Scale	10°F	2°F	0.5	-65 to 2000	↓	Fiber Optic Harness	1000°F to 3000°F	Non-linear Chopped DC	5°F	2°F	10	See Comm.	↓	Sensor Tip 3000°F Maximum Scanner & Photo Detector -65°F to 200°F (Cooled)
19	L.P. Turbine Discharge Total Temp.	T5	E			X		X		X		↓	-65°F to 2000°F	80 MV DC Full Scale	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	
20	Oil Temp.	TL	E	X		X		X				RTD Probe	-65°F to 350°F	Res. Chg. with temp. Platnium	0.2°F	.05°F	0.2	-65 to 400	↓	Piezo Electric Quartz	Same	Variable Freq. at 100K Hz	Same	→	→	→	→	
21	Scavenge Temp.	TLS1 to TLS4	E			X		X		X		↓	-65°F to 400°F	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	→	→	→	→	Use Temperature Rise for Diagnostic Purposes
22	Bearing Race Temp.	BGT1 to BGT2	E			X		X		X		T/C Probe	↓	DC Milli-volts	5°F	1°F	0.5	↓	↓		Eliminate - Use Magnetic Particle Detector							See Text
23	A/B Lightoff Detector	ABI	E		X				X			UV Tube	Off - On	Variable Freq.	10%	1%	1K	↓	↓	Solid State UV Sensor	Off - On	Variable Freq.	5%	1%	1K	1000	30	Reduce Size and Increase Temp. Capability w/o Cooling

IEIS SENSOR MATRIX

PARAMETER							PURPOSE			INTERFACE	CURRENT STANDARD								PROJECTED NEED								
NUMBER	NAME	SYMBOL	LOCATION	DISPLAY	ENGINE CONTROL	FAULT DET/ISOL	RECORD KEEPING	HEALTH TRENDING	ENGINE CONTROL	IEIS DEDICATED	AIRCRAFT SYSTEMS	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	TYPE	RANGE	OUTPUT SIGNAL	ACCURACY	REPEATABILITY	FREQUENCY RESPONSE HZ	TEMPERATURE °F	VIBRATION g	COMMENTS
24	Foreign Object Strike	FOD	E	X		X		X		X		Piezo Electric Accel.	0 to 1000 g	20 PC per g	5% fs	2% fs	20K	-65 to 400	30	← Same →								Improve Vibration Integrity and Make Externally Removable
25	Mass Unbalance	MUN (2)	E	X		X		X		X		↓	↓	↓	↓	↓	↓	↓	↓	← Same →								
26	Bearing Condition	BRG	E	X		X		X		X		↓	↓	↓	↓	↓	↓	↓	↓	Use Magnetic Particle Detector								
27	Oil Quality	QUALO	E			X		X		X		No Satisfactory Airborne Standard Use GSE Oil Quality Monitor or/and Soap								Magnetic Particle Detector	0 to 1.0 milligrams per hr.	Variable Freq. at 1K Hz	10% fs	3% fs	1	-65 to 400	30	
28	Oil Flow	WLD	E	X		X		X		X		Free Turbine Volumetric	0 to 20 GPM	Variable Freq. & Amplitude	5% fs	2% fs	5	-65 to 400	30	No Projected Need								
29	Oil Level	QL	E	X		X		X				Magnetic Reed SW & Float	0 to 6 GAL	Stepped DC 0 to 300 Ohms	2% fs	1% fs	2	↓	↓	Solid State	Same	Variable Freq. at 10K Hz	← Same →					See Text
30	Main Fuel Flow	WF36	E	X		X		X				Angular Momentum Mass Flow	0.3 to 12 KPPH	Indicator System Output 0-5 VDC	1% fs	0.5% fs	1			Fluidic & Density	↓	Variable Freq's	0.5% fs	0.2% fs	10	Same	Same	
31	A/B Fuel Flow	WF6	E	X		X		X				Angular Momentum Bypass Mass Flow	1 to 70 KPPH	↓	↓	↓	↓			↓	↓	↓	↓	↓	↓	↓	↓	
32	Anti-Ice Flow	WBA1	E		X	X		X		X		Pneumatic Assisted Elec Regulating	On - Off	NA	NA	NA	10			← Same →								Simplification Improvements Needed
33	H.P. Compressor Interstage Bleed Flow	WB27	E			X		X		X		Orifice Pressure Diff. Bourdon	0 to 7 PPS	400 Hz AC Ratio	3% fs	1% fs	↓	↓	↓	Orifice Diff. Pressure Crystal XDCR	Same	Variable Freq. at 100K Hz	Same	Same	Same	Same	Same	
34	H.P. Compressor Discharge Bleed Flow	WB3	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	

IEIS SENSOR MATRIX

PARAMETER: Number	Name	Symbol	Location	PURPOSE: Display	Engine Control	Fault Det/Isol	Record Keeping	Health Trending	Engine Control	IEIS Dedicated	Aircraft Systems	INTERFACE: Type	CURRENT STANDARD: Range	Output Signal	Accuracy	Repeatability	Frequency Response Hz	Temperature °F	Vibration g	PROJECTED NEED: Type	Range	Output Signal	Accuracy	Repeatability	Frequency Response Hz	Temperature °F	Vibration g	Comments
35	Fan Inlet Guide Vane Position	BF	E		X	X			X			LVDT on Actuator	-10^{o} to -25^{o}	AC Sine 400 Hz Linear	0.5% fs	0.1% fs	100	-65 to 400	30	Magnetic Digital	Same	TTL Serial Digital	10 Bit	2 Bit	Same	Same	Same	LVDT Reliability Marginal Linkage Slop Introduces Additional Errors
36	Core Variable Stator Position	BC	E		X	X			X			↓	-5 to $+35^{o}$	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
37	Jet Nozzle Throat Area	AB	E		X	X			X			↓	600 to 1700 In. Sq.	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
38	Power Lever Angle	PLA	E		X	X			X			Synchro	0 to 130 Deg.	2φ AC 400 Hz Sin/Cos	$.1^{o}$	$.05^{o}$	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
39	Fan Speed	XNL	E	X	X	X		X	X			Reluctance or Eddy Current Pickup	0.9 to 9K RPM	Variable Freq. & Ampl.Appx. Sine Wave	00 NOTE	00 1	10K	↓	↓	←		Same					→	Increase Temperature Capability
40	Core Speed	XNH	E		X	X		X	X			Altenator Winding Output	1.6 to 16K RPM	4.5 to 105V RMS Sine 2440 Hz fs	↓	↓	↓	↓	↓	←		Same					→	
41	Fan IVG Torque Motor Current	BFTM	E			X		X		X		Permanent Magnet PWM EXC	200 MA Peak 0 to Continuous	400 Hz Variable FW SQ Wave	3% fs	1% fs	500	↓	↓	←		Same					→	Ultimate Trend Toward Direct Drive Motors
42	Core IVG Torque Motor Current	BCTM	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓			↓						↓
43	A8 Torque Motor Current	A8TM	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓			↓						↓
44	Main Fuel Torque Motor Current	WF36TM	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓			↓						↓
45	A/B Fuel Torque Motor Current	WF6TM	E			X		X		X		↓	↓	↓	↓	↓	↓	↓	↓			↓						↓
46	Humidity	HUM	E			X		X		X		Chemical Crystal	0 to 100%	Resistance Change	5% fs	2% fs	.05	↓	↓	Thermo-electric Quartz Crystal	Same	Variable Freq. at 100K Hz	2% fs	1% fs	10	Same	Same	

NOTE 1: Accuracy and repeatability are high since the interface electronics counts pulses.

4.0 TECHNICAL DESCRIPTION

Seven major sensor groups, pressure, temperature, vibration, flow, position, speed and current measurement, are included in the sensor matrix. A technical description of each sensor group is given below. Sensor types not falling within a defined group are discussed individually.

4.1 Pressure

As identified in the sensor matrix, two distrinctly different types of pressure sensors are currently used. For engine control measurements, a solid state strain gage type, housed within the engine control protective enclosure, is the accepted standard. This approach is taken to minimize thermal errors and improve reliability. The longer pressure lines required by this approach yield slower response characteristics which is not currently a major concern. Also, solid state strain gage devices require a well regulated 10 VDC excitation.

The more routine pressure measurements are satisfied with a bellows or bourdon type transducer having an electromagnetic ratio transformer type output. These devices are typically lower cost and use standard aircraft 115V 400 Hz excitation.

Considering future requirements for digital interface, higher response time implications of transient condition monitoring and somewhat improved accuracy for some critical performance measurements, frequency output devices such as those being developed by Hamilton Standard and Paroscientific show the greatest promise.

In particular resonating quartz crystal approaches, with further development toward higher temperature capability, appear to have the best collection of potential characteristics. The output is a fixed amplitude variable frequency signal referenced to some baseline frequency. Linearization of the inherent third order performance curve is required but is easily handled in a computer based engine control or performance monitoring system.

4.2 Temperature

Thermocouples (T/C), resistance temperature detectors (RTD) and optical pyrometers are the currently accepted devices for measuring temperature on engines. Thermocouples and RTDs are typically immersion probe devices and are rugged in design to minimize the possibility of engine damage due to probe breakage. Response times are therefore slow, i.e. in the range of seconds. For thermocouples, especially, interfacing cabling and electronic circuitry must be carefully designed to minimize errors.

The optical pyrometer, used for measuring high pressure turbine blade temperature, is now a fully accepted device for engine application. The output signal is coupled to the engine control for limiting fuel input, thereby preventing over temperature conditions. The silicon photodetector used is sensitive down to surface temperatures of approximately 1000°F. A single probe thermocouple, attached to the pyrometer, detects gas temperature below 1000°F. Output of the pyrometer is highly nonlinear. Special linearization and scaling circuitry is required for combining pyrometer and T/C signals to develop a display signal that varies smoothly over the entire gas temperature range.

The optical pyrometer is a relatively new device and is projected for universal application in the 1980 to 1985 time period. Further expansion of its fast response capability through improved signal processing will make possible detection of both hot and cold blade problems. Extension of the operating range to 400°F is desirable, but needed only for display purposes.

Three other temperature sensing techniques expected to be further developed and applied to engines are described below.

4.2.1 Wall Mounted System

The need for wall mounted (non-immersion) sensors has been well established. Wall mounted techniques do not introduce mechanical breakage and secondary damage risks, do not introduce flow distortions and, in general, provide higher speed of response compared with immersion types.

Three non-immersion sensor techniques have been developed to varying degrees for gas path analysis in laboratory environments. These techniques involve measurement of acoustic velocity, particle velocity (laser technique) and radio active absorption rate and provide static temperature, stream velocity and gas density data respectively. All gas parameters can be accurately calculated using standard gas equations.

In the near term, the acoustic velocity technique (Figure D-1) appears to be the only one that could be applied with moderate development effort. If this technique was supplemented with a standard static pressure measurement (non-immersion) and a total pressure measurement (ports located in the leading edge of stator vane at each stage of interest), a practical non-immersion system would be possible. Computer calculation of the following terms would be necessary to obtain total temperature.

$$T_{STATIC} = \frac{A^2}{C}$$

$$T_{TOTAL} = T_{STATIC} \left(\frac{P_{TOTAL}}{P_{STATIC}}\right)^K$$

Where T = Temperature, P = Pressure, A = Acoustic Velocity,
C = Constant and K = Constant

The acoustic velocity technique deserves further study also because of possible application in liquid level sensors for distance measurement. Measurement of static temperature by a secondary means would be necessary for compensation purposes.

4.2.2 Resonating Quartz Crystals

A further application of the resonating quartz crystal technique, previously described for pressure measurement, will be developed for temperature measurement such as oil temperature rise. The approach and output signal will be similar except that loading force will be thermally induced. The temperature sensor will be significantly smaller than the pressure transducer.

4.2.3 Fiber Optic Harness

Immersion type probes still appear to be the only practical approach for gas temperature measurement in the combustion products stream. In one relatively new harness approach, sapphire light pipe probes are used as integral target and light conducting elements. Outputs are coupled to a photo detector through an optical scanner and are handled in a manner similar to the pyrometer. Advantages of this approach are simplicity, ability to monitor each probe in the harness, temperature measurement capability to 3000°F and higher speed of response compared with thermocouples.

4.3 Vibration

The vibration parameter will continue to be sensed with piezoelectric accelerometers. The optimum approach involves attaching the accelerometer to the housing structure of critical bearings to obtain the best signal to noise ratio and avoid phase shift problems associated with other structural resonances.

In engines where buried accelerometers have been applied, significant reliability problems have developed, primarily because of the vulnerability of the lead and connector design. Future designs must solve this problem and also evolve into a more maintainable, externally removable, dipstick concept.

4.4 Flow

Fluid driven, non-electrically powered, three wire, angular momentum type mass flow transmitters are the accepted standard for measurement of fuel flow rate. Using this instrument, mass flow rate is a function of the time between the two pulses generated.

Future devices will employ fluidic principles to obtain volumetric flow rate and utilize density measurement to allow calculation of mass flow rate. These devices will both produce frequency type output signals and have no moving parts.

4.5 Position

Linear variable differential transformers (LVDT) of various sizes are widely used on current engines as position feedback elements. These devices require an AC voltage excitation and produce an AC output signal that is linear with core position and excitation level.

Development work being conducted on a magnetic type digital angular position transducer is sufficiently promising to project this device as available for application in the 1980 to 1985 time frame. The basic output from this device is in parallel format but a companion program involving parallel to serial conversion should result in a total device which produces a TTL compatible serial digital signal when interrogated. This approach is expected to see application in linear position transducers as well.

4.6 Speed

Speed signals will continue to be obtained from variable reluctance and eddy current type sensors for power turbine readout and alternator windings for gas generator turbine readout per current practice. These devices are electromagnetic in nature and hermetically sealed where possible. Some emphasis on increasing the upper operating temperature limit will be necessary.

4.7 Torque Motor Current

A permanent magnet torque motor device will continue as the interface between the electronic engine control and the hydromechanical force producing system for activating variable geometry engine elements. In the near future these motors will be interfaced with fail fixed type servo valves for overall system reliability improvements. Motor excitation is a pulse width modulated current and the actual measurement of this current must be handled by a timing technique.

4.8 Oil Quality

Recent activities in the tribology field indicate that valuable information on bearing health is contained in the form of magnetic debris in the lube oil. Oil monitoring techniques currently available for on engine application, ranging from electro-optical to gap and screen shorting schemes, are not considered adequate for a number of reasons including sensitivity to air bubbles, sensitivity to temperature, high pressure drops, poor particle collection efficiency and false alarms. The ultimate device, short of a digital sensor, is one that has an 80% minimum collection efficiency and produces a frequency output that is a function of magnetic debris generation.

4.9 Thrust

Thrust is perhaps the most difficult engine performance parameter to measure directly in an airborne situation. Indirect measurements which require sensing nozzle static pressure and throat area (for choked condition) probably can not be accomplished to the desired accuracy. Test cell techniques employing thrust load measuring cells or "thrust link" devices are the projected technology direction, however, a significant amount of sensor development and engine suspension changes will be required before accurate thrust measurement becomes a reality.

4.10 Humidity

The sensitivity of engine performance parameters to the complete range of humidity level, except for rain injection, is in the order of several percent. The need for humidity measurement is minimal, except for projecting icing conditions.

A device employing vibrating quartz crystal techniques and thermoelectric cooling to dew point temperatures is being developed and is projected as the humidity sensor for the future.

4.11 A/B Lightoff

A McGraw Edison UV tube and electronic interface system is the accepted standard device for detecting afterburner lightoff. For the future, smaller, more rugged and higher temperature range UV detectors, requiring lower excitation voltages, have been developed by General Electric Company. The output signal is a count or "breakdown" rate which is a function of UV intensity.

5.0 RECOMMENDATIONS

The following future activities are recommended:

1. This survey did not encompass cost vs. reliability studies of the identified IEIS parameters. Adding a sensor to an engine tends to decrease engine reliability and increase engine cost. Improved system readiness and decreased cost over system life are not necessarily the result. Some hard decisions limiting sensors to specific problem areas will likely be necessary.

An objective follow-up study should be conducted to quantify the reliability/cost relationship for each potential engine problem and proposed detection system. This study should be based on actual maintenance data from several, in service engines. Provisions are needed for evaluating the ability of the condition monitoring system to accurately detect a problem and to generate a low percentage

of false alarms. Reliability improvement of both the engine and the condition monitoring system, improvements in maintenance efficiency, and initial procurement costs should be considered. The expected results of this study would be guidelines for parameter selection, sensor cost and reliability objectives.

2. Except for pressure transducers, a clear path to digital sensor hardware is not evident. Greater effort in developing digital sensors is needed.

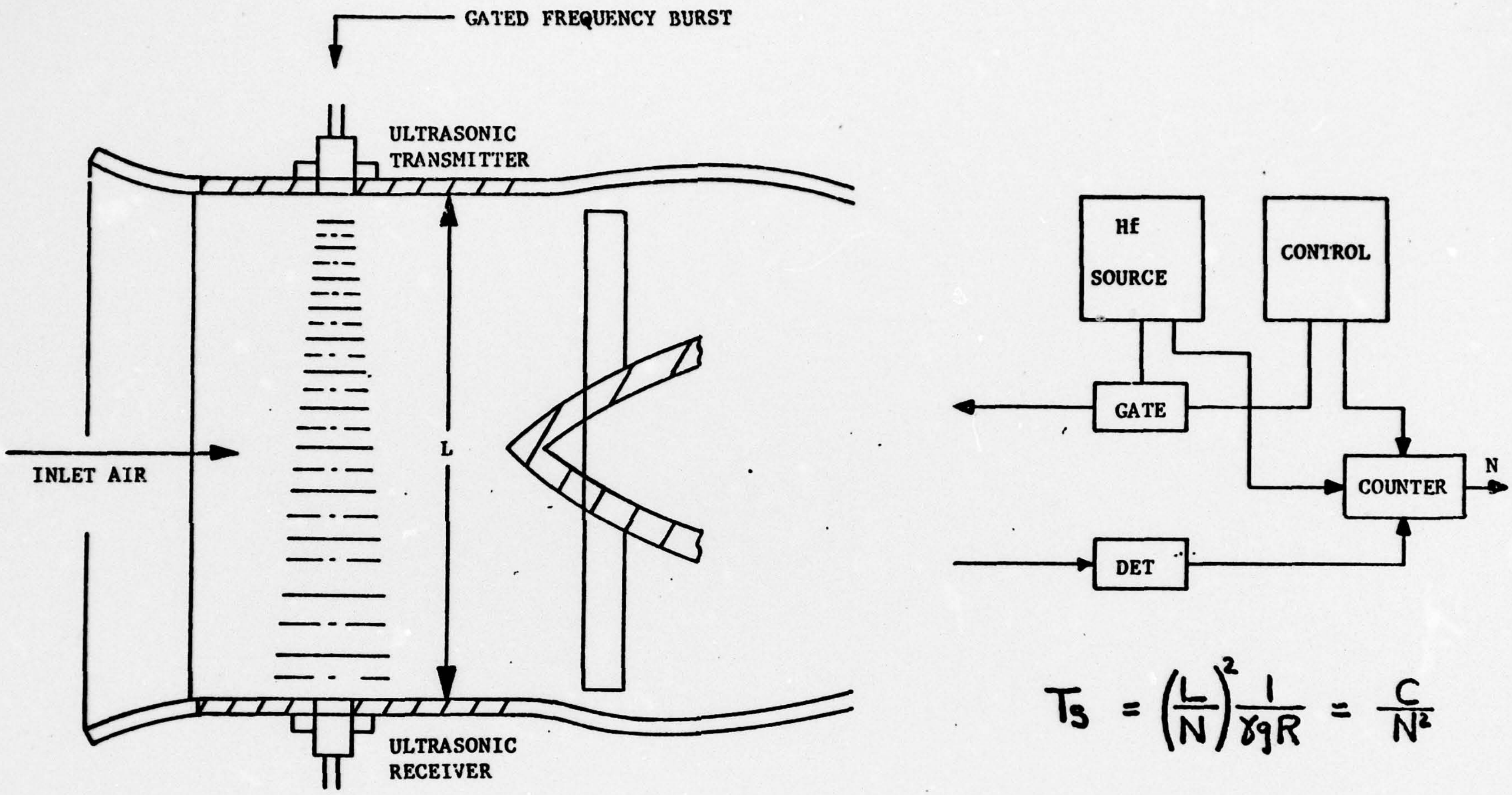
3. Three sensor techniques uncovered as a result of this survey have the potential to provide significantly improved performance or new capability. The three techniques follow:

- Acoustic velocity, a non-immersion technique for measuring static temperature
- Magnetic particle detector for lube oil sensing of bearing wear condition
- Integral sapphire light pipe/target hot gas temperature measurement

Development programs for these techniques should be initiated.

4. Development effort should be applied toward extending the optical pyrometer temperature response to 400°F from the present 1000°F. Also, the device should utilize fiber optic transmission techniques.

5. A direct approach to thrust measurement is needed. The development effort should be applied to a measurement system which is an integral part of the engine suspension.



$$T_S = \left(\frac{L}{N}\right)^2 \frac{1}{\gamma g R} = \frac{C}{N^2}$$

STATIC TEMPERATURE MEASUREMENT BY SONIC PROPAGATION

FIG. D-1

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